Land Cover Changes and Their Biogeophysical Effects on Climate

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Review

Land cover changes and their biogeophysical effects on climate

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ABSTRACT: Land cover changes (LCCs) play an important role in the climate system. Research over recent decades highlights the impacts of these changes on atmospheric temperature, humidity, cloud cover, circulation, and precipitation. These impacts range from the local- and regional-scale to sub-continental and global-scale. It has been found that the impacts of regional-scale LCC in one area may also be manifested in other parts of the world as a climatic teleconnection. In light of these findings, this article provides an overview and synthesis of some of the most notable types of LCC and their impacts on climate. These LCC types include agriculture, deforestation and afforestation, desertification, and urbanization. In addition, this article provides a discussion on challenges to, and future research directions in, assessing the climatic impacts of LCC.

KEY WORDS land cover change; climate; biogeophysical impacts

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1. Introduction

Land cover change (LCC) has significant impacts on the earth's climate, hydrology, water resources, soils, and biota (Foley *et al.*, 2003b; Lambin *et al.*, 2003; DeFries *et al.*, 2004; Twine *et al.*, 2004; Scanlon *et al.*, 2005, 2007, Zhang and Schilling, 2006; Cotton and Pielke, 2007; Pereira *et al.*, 2010). Despite some uncertainties in the magnitude of the impacts, it is increasingly recognized as an important forcing of local (Landsberg, 1970; Balling, 1988; Segal *et al.*, 1989b, Rabin *et al.*, 1990; Balling *et al.*, 1998; Arnfield, 2003; Campra *et al.*, 2008; NRC, 2012), regional (Barnston and Schickedanz, 1984; Zheng *et al.*, 2002; Foley *et al.*, 2003a; Mohr *et al.*, 2003;

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Oleson *et al.*, 2004; Voldoire and Royer, 2004; Gero *et al.*, 2006; Ray *et al.*, 2006; Betts *et al.*, 2007; Costa *et al.*, 2007; Abiodun *et al.*, 2008; Klingman *et al.*, 2008; Lee *et al.*, 2008; Nuñez *et al.*, 2008; Kvalevåg *et al.* 2010; Hu *et al.*, 2010), and global climate (Franchito and Rao, 1992; Wu and Raman, 1997; DeFries *et al.*, 2002; Kabat *et al.*, 2004; Avissar and Werth, 2005; Feddema *et al.*, 2005; *NRC*, 2005; Gordon *et al.*, 2005; Cui *et al.*, 2006; Ramankutty *et al.*, 2006; Takata *et al.*, 2009; Sacks *et al.*, 2009; Puma and Cook, 2010; Davin and Noblet-Ducoudré, 2010; Strengers *et al.*, 2010; Lee *et al.*, 2011; Lawrence *et al.*, 2012). As with carbon dioxide (CO_2), LCC affects the climate system on multi-decadal time scales and longer. In a recent global-scale modelling study, Avila *et al.* (2012) demonstrated that impacts of LCC on indices of temperature extreme were equal to the impacts of doubling of CO_2. In some regions, impacts were similar to forcing of CO_2 while in others they were opposite. Hence, LCC can dampen or enhance the impacts of increasing CO_2 and as a result, it would not be prudent to explain future changes in temperature extremes and other climatic metrics only by increasing CO_2. LCC is, thus, of primary concern in any assessment of climate processes, and involves land surface conversions such as the following: forest to agriculture, reforestation of formerly agricultural areas, afforestation, grassland to irrigated agriculture, rural to suburban, and suburban to fully built-up. Ramankutty and Foley (1999) noted that approximately 12 million km^2 of forests and woodlands have been removed globally since 1700 AD. They estimated that about 18 million km^2, or 11% of the global land area, is currently under farming. This is approximately the size of the entire South American continent (Ramankutty and Foley, 1999). An example of agricultural expansion over the last 500 years can be found in Figure 1. In 2000, livestock grazing represented 22% or 28 million km^2 of the global land area (Ramankutty *et al.*, 2008), which can trigger desertification in semi-arid regions (NRC, 1992). Moreover, Hansen *et al.* (2008; 2010) estimated that there has been 0.27 million km^2 of humid tropical forest loss and 1.10 million km^2 global gross forest cover loss between 2000 and 2005.

These transformations of the Earth's surface fundamentally alter the fluxes of solar and thermal infrared radiation, sensible, and latent heat, the movement of water between the sub-surface and atmosphere, and the exchange of momentum between the land-surface and atmosphere. Alterations such as these occur on spatial scales ranging from the patch or micro- (10^{-2} to 10^3 m) to sub-regional (10^4 to 2×10^5 m) scales (e.g. Anthes, 1984; Oke, 1987) (Figure 2). They may result in modifications of surface albedo, which also alters the near surface energy balance (Zeng and Neelin, 1999; Hoffman and Jackson, 2000; Berbet and Costa, 2003; Zhang *et al.*, 2009b) and the thermal climate (e.g. Oke, 1987; Bonan, 2001, 2008a; Juang *et al.*, 2007). The physical climate modifications manifest as spatial heterogeneities of temperature, humidity, and wind speed. High or low albedo may result in lowered or increased temperature, respectively, due to greater reflection of shortwave radiation or, conversely, higher amounts of shortwave radiation absorption (e.g. Otterman, 1974; Otterman *et al.*, 1984; Lofgren, 1995; Sailor, 1995, Bonan, 2008a). Increased transpiration from a vegetated area also means increased and decreased fluxes of latent and sensible energy, respectively, and a resultant lowering of surface maximum temperatures (e.g. Barnston and Schickedanz, 1984; Geerts, 2002; Ter Maat *et al.*, 2006; Kueppers *et al.*, 2007; Biggs *et al.*, 2008; Ozdogan *et al.*, 2010). In addition, modified climatic phenomena have been observed along and near the boundaries of land cover type transitions, with horizontal gradients of climate variables intensifying, and an alteration of meso-scale vertical circulations within the planetary boundary layer (PBL) that enhance the vertical movement of air (e.g. Segal and Arritt, 1992; Weaver and Avissar, 2001). These greater upwards vertical motions in the PBL may be realized through convective cloud development, and even precipitation, given favourable larger-scale atmospheric conditions. The latter include weak stability and slow background synoptic winds or winds that blow parallel to landscape boundaries (Carleton *et al.*, 2001; Pielke, 2001; Weaver and Avissar, 2001).

Given this context, the primary aim of this article is to review the role of LCC in the climate system. We particularly focus on biogeophysical impacts of LCC. Examples of biogeophysical properties include surface roughness, leaf area index (LAI), vegetation stomatal resistance, and albedo. LCC leads to modifications of these properties resulting in changes in energy, moisture and momentum fluxes. Highlighted examples of impacts include both long-term systematic changes (e.g. agricultural land use change, deforestation, reforestation and afforestation), and short-term abrupt changes (e.g. rapid urbanization). The literature reviewed includes both observational and model-based studies. Finally, we provide a synthesis of results from these studies and discuss critical challenges in LCC-climate research, and make a series of recommendations related to better detecting LCC from observed climatic records and improving modelling approaches for understanding climate impacts of LCC.

2. The role of LCC within the climate system

As indicated above, changes in land cover result in alterations to surface moisture, heat, and momentum fluxes, as well as trace gas exchanges such as CO_2. These changes result in a different PBL structure, cloud cover regime, and indeed all other aspects of local and regional weather and climate (Pielke and Avissar, 1990; Rabin *et al.*, 1990; Pielke, 2001; Fu, 2003; Wang *et al.*, 2009). If sufficiently large areas are affected, then changes in climate occur not only locally, but also in regions remote from the original landscape modification (e.g. NRC, 2005; Cui *et al.*, 2006; Niyogi *et al.*, 2010; Snyder, 2010).

Given this context, the surface energy and moisture budgets for bare and vegetated soils are critical to

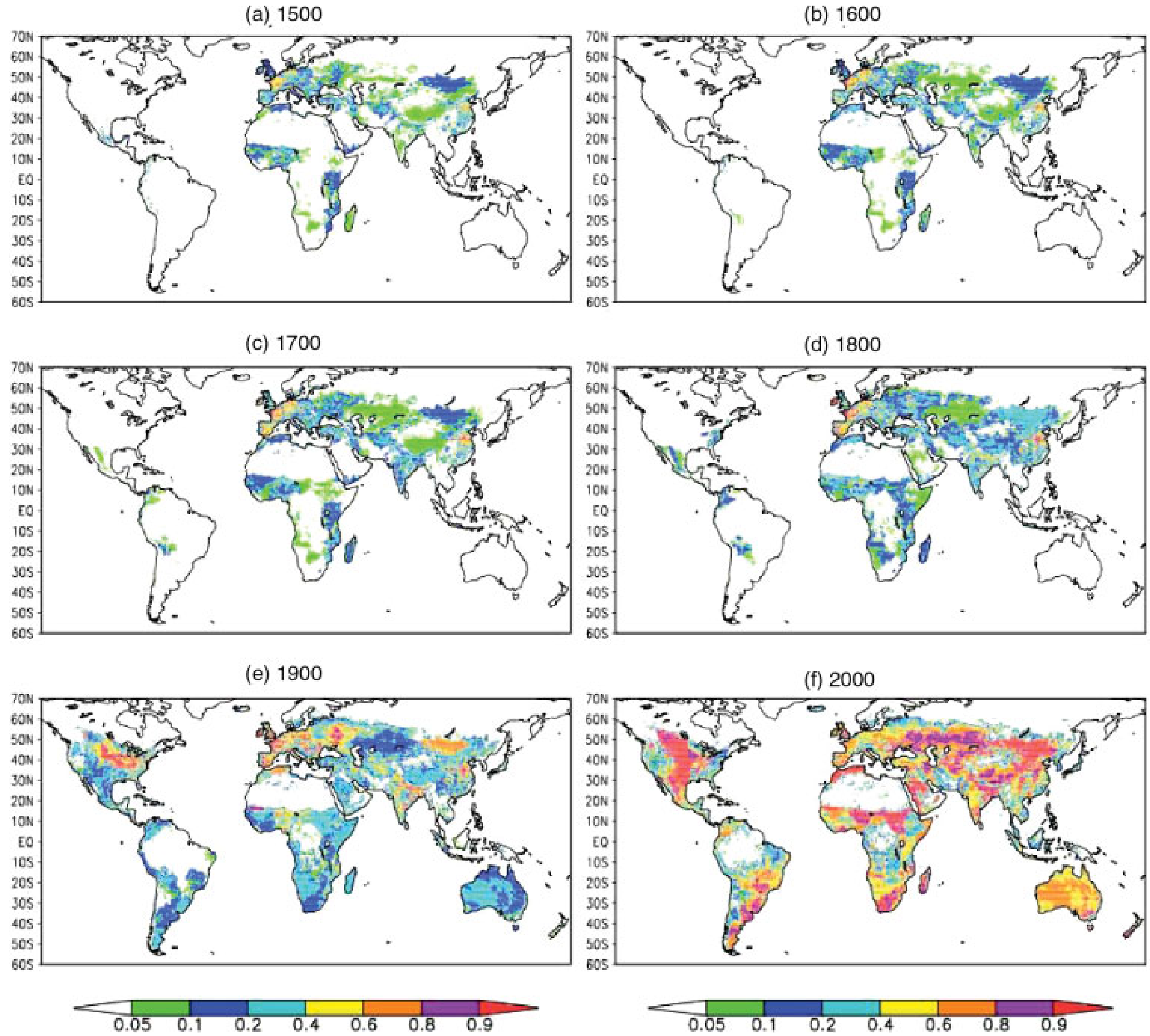

Figure 1. LCC for various time periods. Pasture or crop lands are presented as a fraction. Source of the data is http://luh.unh.edu. Refinement of the data has continued (e.g. much of central Australia is ungrazed or low density grazing and shown as pasture) (Source: Pielke *et al.*, 2011).

understand the impacts of LCC, and can be written after Pielke (2001):

$$R_N = Q_G + H + L(E + T) \tag{1}$$

$$P = E + T + RO + I, \tag{2}$$

where R_N represents the net radiative fluxes $= Q_s(1 - A) + Q_{LW}^{\downarrow} - Q_{LW}^{\uparrow}$; Q_G is the soil heat flux; H is the turbulent sensible heat flux; $L(E + T)$ is the turbulent latent heat flux; L is the latent heat of vapourization; E is physical evaporation (conversion of liquid water into water vapour by non-biophysical processes, such as from the soil surface and from the surfaces of leaves and branches); T is transpiration (the phase conversion to water vapour, by biological processes, through stoma of plants); P is the precipitation; RO is runoff; I is infiltration; Q_s is insolation; A is albedo; $Q_{LW}^{\downarrow}$ is the downwelling longwave radiation; $Q_{LW}^{\uparrow}$ is upwelling longwave radiation $= (1 - \varepsilon)\, Q_{LW}^{\downarrow} + \varepsilon\sigma\, T_s{}^4$; ε is the surface emissivity; σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}); and T_s is the surface temperature. The direction of the fluxes is conventionally defined such that receipt at the surface is positive and loss from the surface is negative. Equation (1) is a budget equation, however, the sources and sinks need to be of opposite sign.

Equations (1) and (2) are not independent of each other. A reduction in E and T in Equation (2), e.g. increases Q_G and/or H in (1) when R_N does not change. Reduced E and T can occur, e.g. through clear-cutting of a forest and the subsequent increase in runoff. The precipitation rate and type also influence how water is distributed between runoff, infiltration, and interception by plant surfaces.

Any LCC that alters one or more of the variables in Equations (1) and (2) has the potential to affect the climate directly. For instance, a decrease in albedo (i.e. a darkening of the surface) by afforestation or irrigated agriculture, increases R_N and thus makes more energy

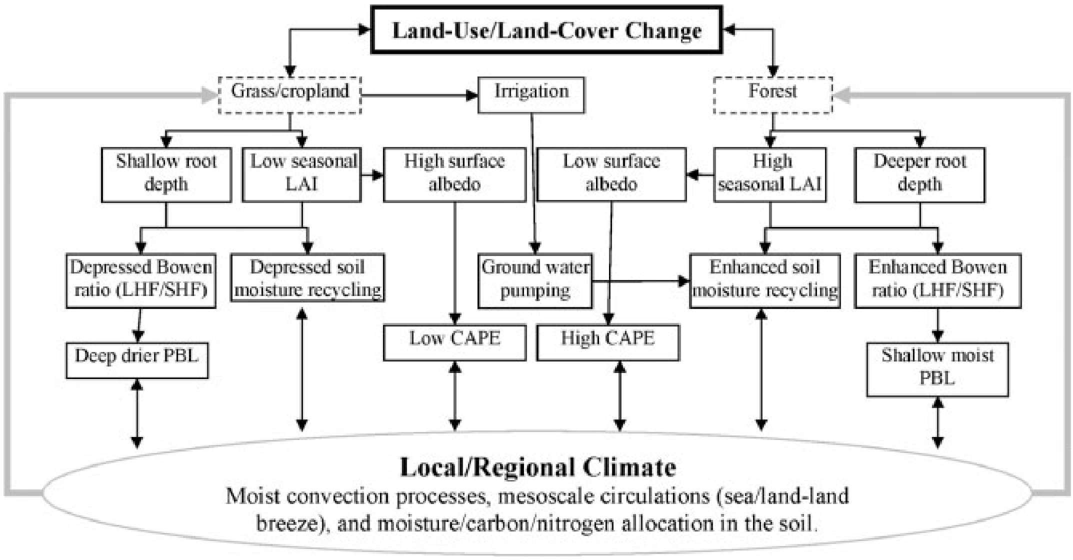

Figure 2. Conceptual model of the impacts of LCC on local and regional climate (Source: Pielke *et al.*, 2007).

available for Q_G, H, E, and T. These changes also modify energy partitioning amount into H versus E and T or Bowen Ratio $(=H/[L(E+T)]$, Bowen, 1926; Oke, 1987). In other words, lower Bowen ratio refers to a moist environment. Once the surface energy budget is altered, fluxes of heat, moisture, and momentum within the PBL are directly affected (Segal *et al.*, 1989a; Douglas *et al.*, 2006). Local (meso-scale) and regional wind and other weather patterns can subsequently be affected due to horizontal variations in H and PBL depth (Segal and Arritt, 1992; Leeper *et al.*, 2009). In addition to albedo and partitioning of surface fluxes, the surface biophysical characteristics can also impact the thermal inertia/heat capacity of the land surface. It is noted that nighttime temperatures are more sensitive to heat capacity (see McNider *et al.*, 2005; Shi *et al.*, 2005). High water contents in soils, such as from irrigation, can increase heat capacity as can highly vegetated areas.

Similar budget equations (comparable to Equations (1) and (2)) can be written for carbon and nitrogen fluxes (e.g. Parton *et al.*, 1987; Running and Coughlan, 1988). The carbon budget involves the assimilation of CO_2 into carbohydrates within vegetation, the respiration of CO_2 from plants and animals, decay of animal and plants, industrial and vehicular combustion processes, outgassing from oceans and other water bodies and volcanic emissions. The nitrogen budget has also been segmented into its different components, e.g. by Galloway *et al.* (2004) and Lamarque *et al.* (2005). Each of these budgets will be changed if any characteristic of the land surface is altered. These include both land management caused changes (e.g. deforestation or alterations in the type of agriculture) and phenological changes due to drought and other environmental stresses to vegetation (e.g. increased temperature, attacks by pests and disease, etc.).

The surface energy and moisture budgets and the carbon and nitrogen budgets are closely coupled. Changes in the energy and moisture budget alter the carbon and nitrogen budget (and that of other trace constituents), while alterations in carbon and nitrogen (and other trace gases and aerosols) change the surface energy and moisture budgets. The primary link in the coupling of these fluxes is the transpiration of water vapour through the stoma of plants, which influences changes in the energy budget, and is also involved in the assimilation of carbon into plant leaves, roots, and stems. If the amount of actively growing plant biomass changes, this alters the transpiration of water vapour into the atmosphere and thus the amount of carbon that is assimilated. The amount of nitrogen compounds and other trace nutrients affect plant growth and vitality, as determined from parameters such as biomass, leaf-area index, and photosynthesis. The intimate coupling by feedback processes of the surface budgets is a fundamental regulator of the climate system. In short, land management practices and resulting LCCs that alter any one of these budgets necessarily alter all of them.

There are a number of model based studies conducted addressing comparative biogeophysical and biogeochemical impacts of LCC (e.g. Brovkin *et al.*, 2004; Matthews *et al.*, 2004; Lawrence *et al.*, 2012). Brovkin *et al.* (2004) and Matthews *et al.* (2004) found cooling due to biogeophysical impacts while warming due to biogeochemical impacts. Brovkin *et al.* (2004) have reported that globally averaged biogeochemical change related warming is 0.18 °C while biogeophysical change related cooling is 0.26 °C (net cooling 0.08 °C). However, they have also noted that regional impacts can be significant. On the other hand, Matthews *et al.* (2004) noted a net global warming of 0.15 °C for the combined impact.

The following sections highlight the biogeophysical climatic impacts of some of the most notable types of LCC. We include discussion of the impacts of agricultural land use, deforestation and afforestation, desertification, and urbanization. The discussion within each subsection flows from smaller to larger scales. In addition, modelling studies are identified and the rest represent observational data based research.

3. Meso-, regional-, sub-continental- and global-scale impacts

3.1. Changes in fluxes and precipitation

At the meso-scale, LCC-driven urbanization impacts energy fluxes and balance (see the review by Arnfield, 2003). In most of the cases, urbanization results in replacement of natural vegetation with a built environment. As a result, energy flux is dominated by sensible energy flux that leads to development of the Urban Heat Island (UHI). In urban areas the maximum sensible energy flux can be several orders of magnitude higher than latent energy flux (e.g. Grimmond and Oke, 1995; Grossman-Clarke *et al.*, 2010; Hanna *et al.*, 2011). However, the relative magnitude of partitioning into sensible energy flux varies with season, geographical location of the urban area, and within urban area land use variations. The latter can be the central business district (nearly free of vegetation) versus residential area (can be substantially vegetated) (e.g. Masson *et al.*, 2002; Lemonsu *et al.*, 2004; Offerle *et al.*, 2005, 2006; Kawai *et al.*, 2009; Grossman-Clarke *et al.*, 2010; Hanna *et al.*, 2011; Loridan and Grimmond, 2012). In humid temperate regions, the removal of the natural forest and wetlands has resulted in a reduction of transpiration and evaporation and an increase in sensible energy fluxes and the Bowen ratio (e.g. Shepherd, 2006; Caldwell *et al.*, 2012). In arid and semi-arid regions, by contrast, urban areas typically have irrigated landscapes such that the latent energy flux is much larger than the natural desert or steppe landscape (e.g. Segal *et al.*, 1988).

These changes in convective fluxes associated with urban land use also influence meso-scale atmospheric dynamics and stability profiles in such a manner that precipitation is affected (Figure 3). A wealth of historical and contemporary literature shows that UHI-destabilization, canopy-related surface roughness, and/or pollution can independently or synergistically modify, amplify, reduce, or initiate precipitating cloud systems (e.g. Landsberg, 1970; Changnon *et al.*, 1981; Bornstein and Lin, 2000; Shepherd *et al.*, 2002, 2010a, 2010b; Niyogi *et al.*, 2006; Shepherd, 2006; Kaufmann *et al.*, 2007; Mote *et al.*, 2007; van den Heever and Cotton, 2007; Rose *et al.*, 2008; Stallins and Rose, 2008; Trusilova *et al.*, 2008; Hand and Shepherd, 2009; Shem and Shepherd, 2009; Ashley *et al.*, 2012; Mitra *et al.*, 2011; Niyogi *et al.*, 2011). The overwhelming majority of these studies reveal a link between urban areas, convection enhancement, and increased precipitation.

Lei *et al.* (2008), Kishtawal *et al.* (2010) and Niyogi *et al.* (2010) suggested that the heavy rainfall trend is greater over the urban regions of India compared to non-urban areas and this can be verified by both *in situ* and satellite datasets. Mitra *et al.* (2011) and Niyogi *et al.* (2011) noted that increased sensible heat flux, convergence, atmospheric destabilization, and resultant modified atmospheric flow patterns play an important role in enhancing precipitation. However, details of the mechanisms and pathways are not fully understood (Shepherd *et al.*, 2010b).

In a modelling study, Trusilova *et al.* (2008) found statistically significant increases in winter rainfall in

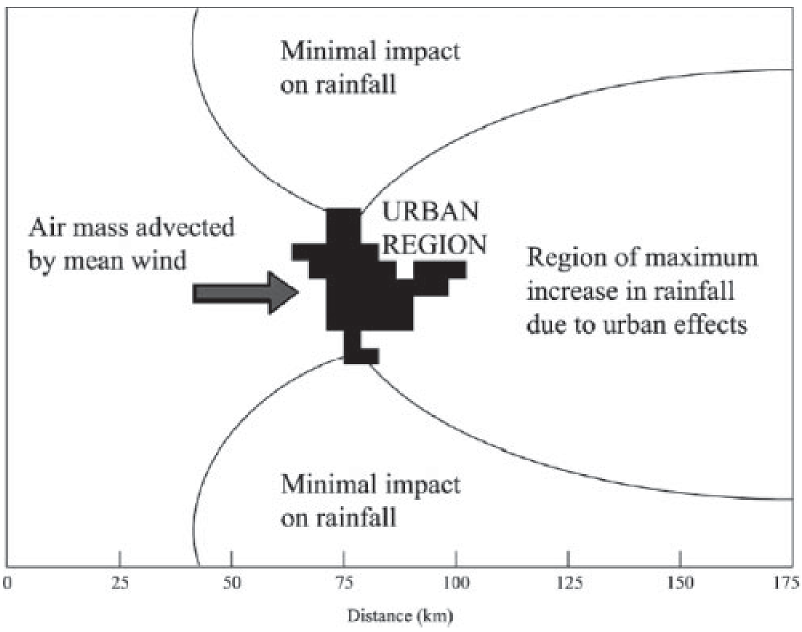

Figure 3. Idealized diagram showing the region of maximum expected rainfall increases due to urban effects located downwind of the city centre. Minimal impact of urban land use on precipitation is observed in the regions perpendicular to the mean wind vector (an adaptation from Shepherd *et al.*, 2002).

Europe in their urban simulations as compared to the pre-urban settlement simulations. UHI-induced enhancement of convection was partly responsible for increased winter precipitation. Three observational and model-based studies in China examining urban effects on rainfall found decreased cumulative rainfall (Guo *et al.*, 2006; Kaufmann *et al.*, 2007; Zhang *et al.*, 2009a). However, these studies did not consider the effects of atmospheric pollution. Smaller cloud droplet size distributions and suppressed rainfall have been linked to increased aerosol concentrations from anthropogenic sources over and downwind of urban areas (Rosenfeld, 1999, 2000; Givati and Rosenfeld, 2004; Lensky and Drori, 2007). The above results suggest that urban forcing on atmospheric dynamics, thermodynamics, energy exchanges, cloud microphysics, and composition need to be explicitly represented in future modelling systems from local to global scales (Jin *et al.*, 2007; Shepherd *et al.*, 2010b).

Also on the meso-scale, except for vegetated surfaces, the replacement of one land cover type (e.g. grassland, forest) by agriculture (rainfed and irrigated) alters not only the radiative and thermal climates noted earlier, but also the moisture budget (Adegoke *et al.*, 2003, 2007). In particular, the substitution of crops that readily lose moisture to the atmosphere, such as corn (maize) and soybeans in the Midwest United States, may cool the surface sufficiently during daytime hours in summer to promote a downward flux of sensible heat, in contrast to nearby natural vegetation areas which tend to better conserve water (e.g. Hatfield *et al.*, 2007). This 'oasis effect' has been implicated in recent observed increases in summertime extreme dew-point temperatures, and reduced maximum temperatures during the 20th century, in parts of the Midwest United States (Bonan, 2001; Sandstrom *et al.*, 2004). This condition may also promote a greater incidence of severe weather (Pielke and Zeng, 1989) due to increased destabilizing impacts of water vapour on the PBL compared to stabilizing effects of evaporation-induced cooling.

A propensity for increased convective cloud and precipitation development in agricultural areas is not solely a function of replacing a natural surface with one that evapotranspires more readily. The crop phenology, ambient atmospheric moisture content, and background synoptic-scale atmospheric circulation (surface winds and free-atmosphere winds) are also critical. For example, Rabin *et al.* (1990) showed, in the southern Great Plains, that when the atmosphere was dry, convective clouds tended to develop first over the dry wheat stubble and later over more moist – and actively photosynthesizing – surfaces that have higher net radiation values. Conversely, when the atmosphere was more humid, convective clouds tended to develop first over the moister vegetated surfaces, and later over drier surfaces.

A similar dependence of the land cover-convection relationship on surface and atmospheric moisture conditions has been observed in the rain-fed corn and soybean areas of the Midwest United States (Carleton *et al.*, 2001; Allard and Carleton, 2010). Moreover, there is a synoptic (i.e. regional-scale) circulation influence on these local land surface-atmosphere impacts that occurs via the advection of moisture by low-level winds, the sign and magnitude of the free-atmosphere vertical motion of air, and the extent to which moisture is trapped within the PBL (e.g. Bentley and Stallins, 2008; Carleton *et al.*, 2008a; Carleton *et al.*, 2008b; Allard and Carleton, 2010). An observational study found that convective precipitation was enhanced in association with the major crop-forest boundaries in the Midwest Corn Belt (Carleton *et al.*, 2008a, 2008b). The findings of these studies highlight the possible role of contrasting phenology and PBL circulations between crop and tree areas in the vegetation boundary–precipitation relationship.

Numerous other studies document LCC induced changes in surface fluxes around the world. For example, Douglas *et al.* (2006) compared modelled water vapour fluxes in India from a pre-agricultural and a contemporary land cover and found that mean annual vapour fluxes have increased by 17% with a 7% increase in the wet season and a 55% increase in the dry season. In a model sensitivity study, Sen Roy *et al.* (2011) found that latent and sensible heat fluxes could be up to about 40 and 80 $\mathrm{W\,m^{-2}}$ higher due to increased and decreased soil moisture, respectively, related to irrigated and non-irrigated conditions in India (Figure 4).

Tuinenburg *et al.* (2011) concluded that large scale irrigation in southern and eastern India may increase local precipitation as a result of land-atmosphere feedbacks. Many other observational and modelling studies for this region that further document changes in precipitation due to LCC include Lohar and Pal (1995), Saeed *et al.* (2009), Niyogi *et al.* (2010), Kishtawal *et al.* (2010), Douglas *et al.* (2009), Lei *et al.* (2008), Lee *et al.* (2009) and Sen Roy *et al.* (2011). Other regions where these effects on regional and sub-continental climate have been shown including the United States (e.g. DeAngelis *et al.*, 2010), Australia (e.g. Nair *et al.*, 2011) and Southeast Asia (e.g. Takahashi *et al.*, 2010). In a detailed observational study, DeAngelis *et al.* (2010) reported that irrigation in the Ogallala aquifer region of the United States has resulted in a 15% increase of July precipitation several hundred miles downwind, including, Indiana and western Kentucky.

Land cover change in southwest Australia impacts boundary layer cloud formation (Lyons *et al.*, 1993; Lyons, 2002; Ray *et al.*, 2003), and micro- (Lyons *et al.*, 2008), meso- and synoptic-scale circulations (Nair *et al.*, 2011). Utilizing observations of surface energy fluxes, Lyons *et al.* (2008) showed a higher possibility of dust devil formation over cleared agricultural landscapes leading to decreases in cloud particle size and reduced probability of rainfall (Junkermann *et al.*, 2009). A modelling study for southeast Australia, a major agricultural region, simulated mean summer rainfall decrease by 4–12% (Figure 3(c) in McAlpine *et al.*, 2009). The authors attributed this change to a significant decrease in evapotranspiration (6.8%), latent heating (7.3%), and total cloud cover, especially low clouds and convective

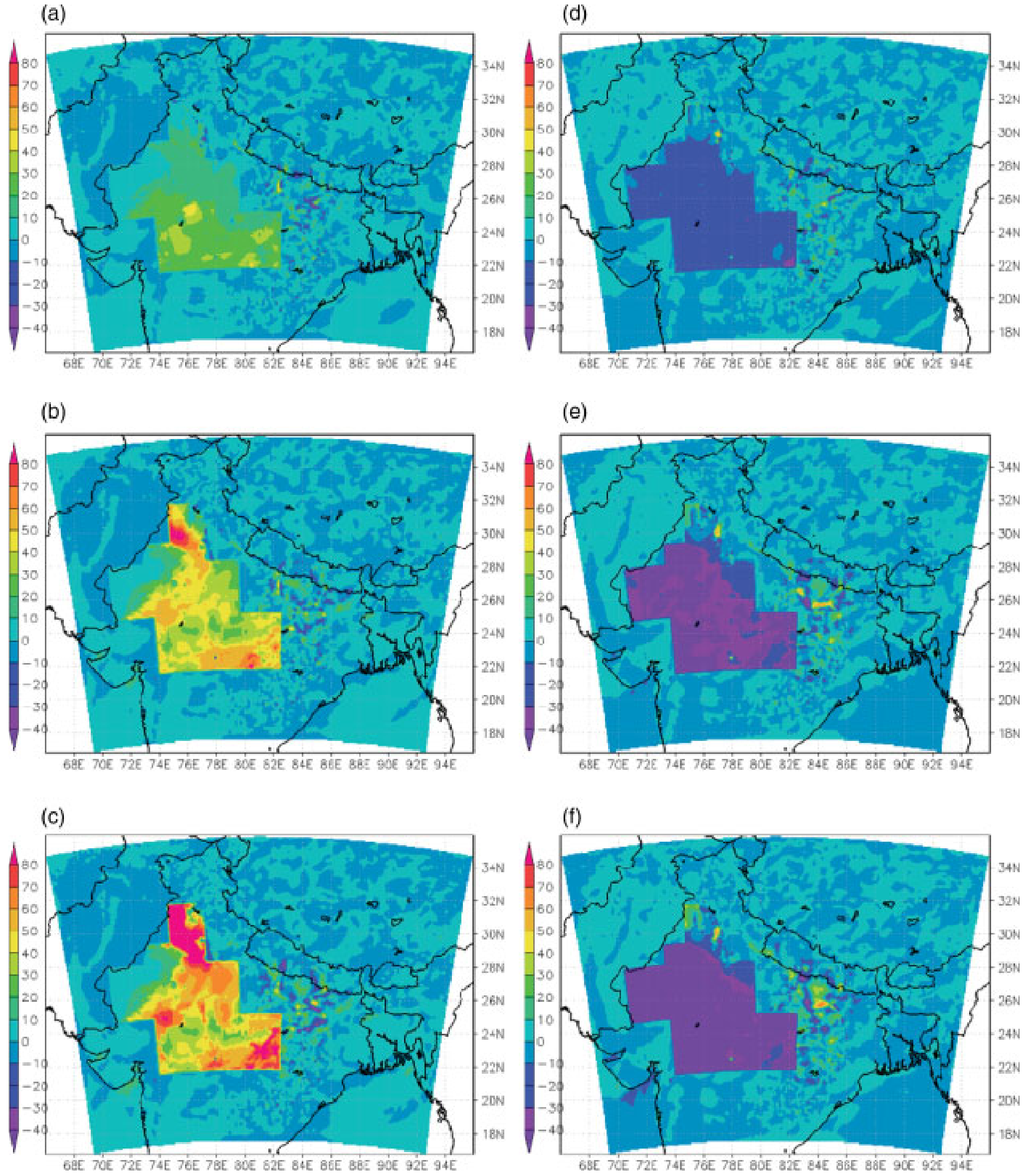

Figure 4. Latent energy flux differences ($W\,m^{-2}$) for 03/23/2000 for relatively drier and wetter (irrigated) conditions. Soil moisture was systematically decreased and increased by 5, 10, and 15% from the current state over irrigated areas. Differences were calculated as: (a) current minus 5% drier, (b) current minus 10% drier, (c) current minus 15% drier, (d) current minus 5% wetter, (e) current minus 10% wetter, and (f) current minus 15% wetter. Various shades of red, orange, and green (a–c) suggest lowering of latent energy flux with increased drying while shades of blue and purple suggest increasing latent energy flux with increased wetting (Source: Sen Roy *et al.*, 2011).

clouds. Analysis of daily rainfall events indicates an increase in the number of dry and hot days, the drought duration, and decreases in daily rainfall intensity and wet day rainfall amounts in southeast Australia, (Figure 2(b); see Deo *et al.*, 2009 and McAlpine *et al.*, 2009 for further details) (Figure 5).

At the large-scale, a global modelling study by Puma and Cook (2010) found increases in precipitation primarily downwind of the major irrigation areas. However, this study also reported that precipitation in parts of India decreased due to a weaker summer monsoon. Similar global effects were found by Guimberteau *et al.* (2011) who noted that irrigation began to significantly increase precipitation starting around 1950 over the Northern Hemisphere mid-latitudes and in the tropics.

Studies of tropical deforestation suggest a decrease in surface evapotranspiration, usually leading to a net decrease in rainfall over the area of deforestation. For example, in a modelling experiment over eastern Amazonia, Sampaio *et al.* (2007) found up to 31 (i.e. 449 mm) and 25% (491 mm) reductions in annual average ET and precipitation, respectively. However, shallow clouds occur more often over deforested areas whereas deep convective clouds favour forested areas. This feature is most evident over the Amazon basin where there is an observed significant climatic shift in shallow cloudiness patterns associated with deforestation during the dry season, when the thermal lifting mechanism is the dominant factor in convective development (Chagnon *et al.*, 2004; Wang *et al.*, 2009). Recently, Spracklen *et al.* (2012) reported

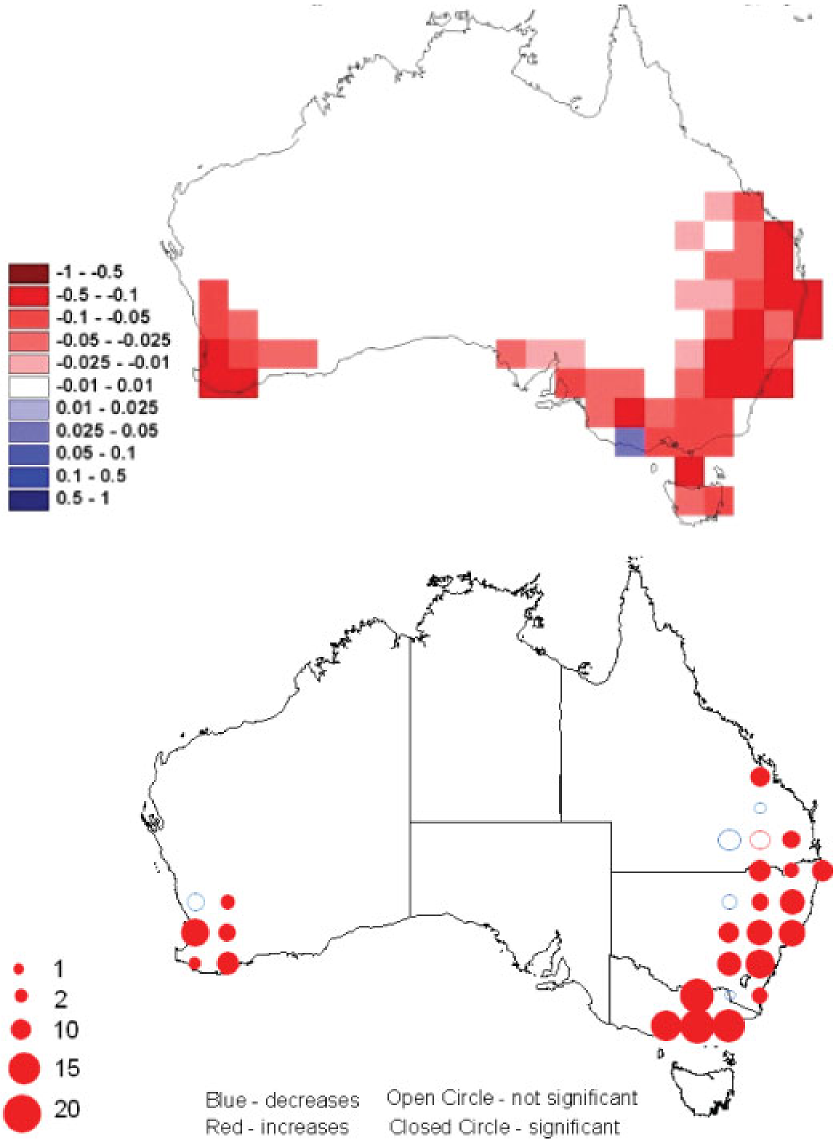

Figure 5. (a) Change in vegetation fraction as represented in the CSIRO Mark 3.5 climate model. (b) Change in the number of consecutive dry days between pre-European and modern-day conditions. Symbols: red for increase, blue for decrease, closed symbols are statistically significant, open symbols are not statistically significant at 90% confidence (Source: McAlpine *et al.*, 2007; Deo *et al.*, 2009).

on the important role of air passage over tropical forests in increasing rainfall. They found that air that has passed over extensive vegetation in the preceding few days produces at least twice as much rain as air that has passed over little vegetation.

Additional examples of tropical deforestation and its climatic impacts, including fluxes and precipitation, can be found in a series of model based research by Roy and Avissar (2002), Snyder *et al.* (2004), Pongratz *et al.* (2006), Werth and Avissar (2002), Abiodun *et al.* (2008), Da Silva *et al.* (2008), Hasler *et al.* (2009), and Davin and Noblet-Ducoudré (2010). Note that variations in the albedo or roughness change can affect the net response to deforestation (Dirmeyer and Shukla, 1996; Sud *et al.*, 1996). Modelling studies have also found similar results for deforestation over tropical Africa (e.g. Kitoh *et al.*, 1988; Xue and Shukla, 1993; Polcher and Laval, 1994a; Sud *et al.*, 1996) and Southeast Asia (e.g. Henderson-Sellers *et al.*, 1993; Polcher and Laval, 1994b; Sen *et al.*, 2004b).

In a model with ideal topography, Dirmeyer (1994) showed that differences in vegetation characteristics affected drought occurrence in mid-latitudes. Restoring vegetation in a GCM to distributions known in Europe, Asia, and North Africa within the Roman Empire (∼2000 YBP) caused summer rainfall in the model to increase in southern Europe and the Atlas Mountains, the lower Nile Valley and the Levant (Reale and Dirmeyer, 2000; Reale and Shukla, 2000). Subsequently, comparison of historical and modern-era LCC modelling studies have been carried out for Europe (e.g. Heck *et al.*, 2001), East Asia (e.g. Xue, 1996; Fu *et al.*, 2004) and Australia (e.g. Narisma *et al.*, 2003; Narisma and Pitman, 2004; McAlpine *et al.*, 2007). It was found that the model responses to LCC in the mid-latitudes are complex. This is because agriculture displaces both forest and prairie/steppes, with opposite effects on climate from the typical changes in albedo and roughness, making the response highly sensitive to the details of the experiment implementation (Pitman *et al.*, 2009).

In general, afforestation and reforestation scenarios show precipitation increases in modelling experiments. Beltrán-Przekurat *et al.* (2012) found, from a modelling study, that in afforested areas over southern South America absolute mean values were higher, up to 0.5 mm day^{-1} in spring and 1.0 mm day^{-1} in summer, compared to current conditions. Using a global circulation model, Xue and Shukla (1996) found a 0.8 mm day^{-1} (or 27%) increases in Sahel precipitation over afforested areas and decreases south of the region.

Using a projected afforestation scenario within a regional climate model over the United States, Jackson *et al.* (2005) noted that changes in summer precipitation were not uniform and depended on location. A general decrease in rainfall was found in afforested areas located in the northern states. Precipitation increased in a few areas such as in Florida and southern Georgia and in other areas, not directly affected by the LCC.

3.1.1. Summary

LCC leads to changes in energy fluxes and their partitioning. At the meso-scale urbanization produces the most dramatic modification in energy partitioning, dominated by sensible energy flux. It is also apparent that these changes, along with other surface biophysical properties, including roughness and albedo, have led to development of convection and or precipitation. However, it is also becoming evident that impacts of urbanization on climate vary widely and are dependent on season, latitude, relative geographical location, and ecological setting. Nonetheless, impacts of urbanization on regional precipitation still need further investigation.

Irrigated agriculture also produces notable changes in surface energy partitioning. In contrast to the impacts of urbanization, the energy flux is dominated by increased latent heating (i.e. lower Bowen ratio). Research on irrigation suggests local, regional, and continental-scale impacts on precipitation. It is also possible that large-scale adoption of irrigation could impact inter-annual precipitation patterns. However, the irrigation-precipitation relationship is complex and the related science is still emerging. Studies on large-scale afforestation also suggest increases in precipitation while tropical deforestation results in lowering of evapotranspiration and precipitation.

3.2. Changes in temperature

One of the most well-known meso-scale features associated with LCC and temperature increase is the UHI (Eliasson and Homer, 1990; Arnfield, 2003; Souch and Grimmond, 2006; Jansson *et al.*, 2007; Yow, 2007; Hidalgo *et al.*, 2008; Trusilova *et al.*, 2009; Georgakis *et al.*, 2010; McCarthy *et al.*, 2010), recognized since at least 1820 (Howard, 1820). Higher surface skin, air, and canopy temperatures relative to the surrounding rural area, typically define the UHI. It is very common that urban development occurs at the expense of existing vegetated area. This type of modification from vegetated permeable surfaces to non-permeable materials such as brick, concrete, and asphalt results in lower latent heat flux and increased sensible heat flux, and hence increased air temperature. For example, Fall *et al.* (2010) found that almost all areas in the continental United States have experienced urbanization-related warming, with values ranging from 0.103 °C (conversion from agriculture to urban) to 0.066 °C (from forest to urban). These results agree with findings from studies by Kukla *et al.* (1986), Arnfield (2003), Kalnay and Cai (2003), Zhou and Shepherd (2009), and Hale *et al.* (2006, 2008).

The UHI-related temperature changes are complex and depend on time of day and year (seasons), latitude, climate regime, circulation feedbacks, surrounding land cover, and size (e.g. Arnfield, 2003; Yow, 2007; Zhou and Shepherd, 2009; Stone *et al.*, 2010). In the mid-latitudes the UHI temperature signal is most pronounced during summer (e.g. Philandras *et al.*, 1999). However, in high-latitude areas it is best developed in the winter months where urban temperatures can be up to 6 °C higher than surrounding rural regions (Hinkel and Nelson, 2007). With negligible to no solar radiation during the winter, this high-latitude UHI is largely due to anthropogenic heat released by maintaining internal building temperatures. In mid-latitude areas, a recent study by Imhoff *et al.* (2010), noted that ecological context may influence the amplitude of the summer daytime UHI. For example, cities built in biomes dominated by mixed forest and temperate broadleaf forest observed up to 8 °C urban–rural temperature difference. These authors (Imhoff *et al.*, 2010) found that urban–rural temperature differences were largest during mid-day in summer. Moreover, urban areas that replaced forest, temperate grasslands and tropical grasslands and savannah experienced 6.5-9.0, 6.3, and 5.0 °C urban–rural temperature difference, respectively.

The UHI-related temperature gradients can be dependent on both land use and urban parameters (e.g. built-up ratio, green surface ratio, sky view factor, etc.) (Oke, 1987). A net surplus of surface energy over urban regions is explained by enhanced ground heat storage and anthropogenic heating, as well as reduced evapotranspirational cooling. Smaller values of the sky view factor below roof level result in decreased longwave radiative loss and turbulent heat transfer, and add to the UHI anomaly (Unger, 2004). Additional discussion of UHI and UHI-related aspects can be found in Satoh *et al.* (1996), Ohashi *et al.* (2009), Fujibe (2010), Murata *et al.* (2012), Aoyagi *et al.* (2012), and Sachiho *et al.* (2012).

Despite UHI's status as a well studied climatological feature, uncertainties related to various processes within UHI have remained. For example, challenges are inherent when considering the multiple-scale interactions between broader global climate change and urban environments. Efforts to mitigate urban biases in the climatological record (Karl *et al.*, 1988; Peterson, 2003) also overlook potential natural climate signals in urban environments.

While some alterations to the land surface, such as UHI, have increased regional temperatures, regional cooling can also occur as a consequence of LCC. In particular, it is found that LCC related to rainfed agriculture has reduced regional temperatures (e.g. Bonan, 1997; Bonan, 2001; Kalnay and Cai, 2003; McPherson *et al.*, 2004; Gameda *et al.*, 2007; Fall *et al.*, 2010; Ge, 2010; Beltrán-Przekurat *et al.*, 2012). On the basis of a large-scale modelling study, Bonan (1997) reported up to 2 °C cooling of summer temperature over the central United States and up to $1.5\,\mathrm{g\,kg^{-1}}$ increase in atmospheric moisture content in much of the United States. He suggested that lowered surface roughness and stomatal resistance, and increased albedo due to replacement of forests with modern vegetation (largely agriculture), resulted in these changes. In a follow-up study, Bonan (2001) found a temporal correlation between expansion of agriculture and lowering of the daily maximum temperature. Subsequently, McPherson *et al.* (2004) and Ge (2010) found low anomalies of observed maximum temperatures for the rainfed winter wheat growing area of Oklahoma and Kansas. McPherson *et al.* (2004) also reported higher dew point temperatures over wheat growing areas compared to the surrounding native grasslands of Oklahoma. These findings were further supported by Sandstrom *et al.* (2004) who reported an increased frequency of days experiencing extreme dew point temperature ($\geq$22 °C) in the central United States and suggested that increased evapotranspiration from croplands (i.e. LCC) to be the primary cause of this increase.

In an observational study, Gameda *et al.* (2007) found significant reductions in mid-June to mid-July maximum air temperatures, diurnal temperature range, and solar radiation of $1.7\,^{\circ}\mathrm{C\,decade^{-1}}$, $1.1\,^{\circ}\mathrm{C\,decade^{-1}}$ and $1.2\,\mathrm{MJ\,m^{-2}\,decade^{-1}}$, respectively, in the Canadian Prairies. They attributed these changes to the increased latent heating associated with increased area under crop cultivation that resulted in lowering of temperature. Moreover, Campra *et al.* (2008) found a 0.30 °C cooling in semi arid Almeira, Spain, associated with changing of pastureland to green house farming, and resultant strong negative radiative forcing (up to $-34\,\mathrm{W\,m^{-2}}$). In summary, it is evident that the adoption of agriculture and resultant LCC has modified the energy balance, albedo, surface roughness, and radiation balance, and led to these changes in temperature.

LCC-related temperature reductions can be further amplified by irrigation. Over recent years, a series of observation and model based studies have been conducted over the key irrigated areas of the United States (Mahmood *et al.*, 2004, 2006; Christy *et al.*, 2006; Lobell *et al.*, 2006a, 2006b; Bonfils and Lobell, 2007; Kueppers *et al.*, 2007, 2008; Lobell and Bonfils, 2008; Jin and Miller, 2011; Sorooshian *et al.*, 2011), India (Sen Roy *et al.*, 2007; Biggs *et al.*, 2008), Australia (Geerts, 2002), and globally (Guimberteau *et al.*, 2011) and have reported lowered growing season temperature in these areas. For example, an observational study by Christy *et al.* (2006) estimated a 0.26 °C cooling trend $\mathrm{decade^{-1}}$ in the daily maximum temperature in California during the growing season while Bonfils and Lobell (2007) reported a 3.2 °C lower daily average temperature. In subsequent modelling studies Kueppers *et al.* (2007, 2008) and Sorooshian *et al.* (2011) reported up to a 7.5 °C cooling of surface temperatures due to irrigation in California. Kueppers *et al.* (2007) noted increased latent energy flux and atmospheric humidity along with these lowered temperatures.

In an observational data-based study, Mahmood *et al.* (2006) found up to a 1.41 °C lowering of maximum temperatures during the post-1945 period over irrigated locations in Nebraska (Figure 6) (Mahmood *et al.*, 2006). Moreover, a cooling trend in long-term extreme maximum temperatures was observed for irrigated locations (Mahmood *et al.*, 2004). This is further supported by increased growing-season dew point temperatures up to 2.17 °C over irrigated areas (Mahmood *et al.*, 2008). Sen Roy *et al.* (2007) reported up to 0.34 °C lowering of growing season maximum temperatures over irrigated areas in India, with individual growing season months showing up to a 0.53 °C decrease. Long-term temperatures in both regions (Nebraska and northwestern India) also showed a negative trend.

As shown in Figure 4, irrigation allows more energy to be partitioned into latent heat than sensible heat (i.e. smaller Bowen ratio), because of increased evaporative cooling, thereby lowering near-surface temperatures (Mahmood and Hubbard, 2002; Mahmood *et al.*, 2004; Kueppers *et al.*, 2007; Sen Roy *et al.*, 2011). The higher soil moisture also lowers albedo and thus increases net radiation and evaporation rate. A recent climate modelling study (Cook *et al.*, 2011) showed that the cooling effects from irrigation exist across the globe and the magnitude of the effects may remain the same or intensify over most irrigated regions under the higher greenhouse gas scenario.

Deforestation and afforestation also impacts temperatures. The consensus parameterization of the tropical deforestation studies was that surface albedo increases and roughness length decreases (Kitoh *et al.*, 1988; Mylne and Rowntree, 1992; Sud *et al.*, 1993). Although these changes have opposite impacts on near-surface air temperature, most studies suggested a net warming (see *Garratt* (1993) for a review of early studies) (Figure 7). A more robust result was a decrease in surface evapotranspiration and significant increase in annual mean temperature (Sampaio *et al.*, 2007). These authors noted up to 4.2 °C and $25\,\mathrm{Wm^{-2}}$ increases in temperature and sensible heat flux, respectively. Impacts of tropical deforestation on temperature can also be found in previously noted modelling studies by Shukla *et al.* (1990), Nobre *et al.* (1991), Snyder *et al.* (2004), Pongratz *et al.* (2006), Werth and Avissar (2002), Abiodun *et al.* (2008), Da Silva *et al.* (2008), and Davin and Noblet-Ducoudré (2010). Further overview of the

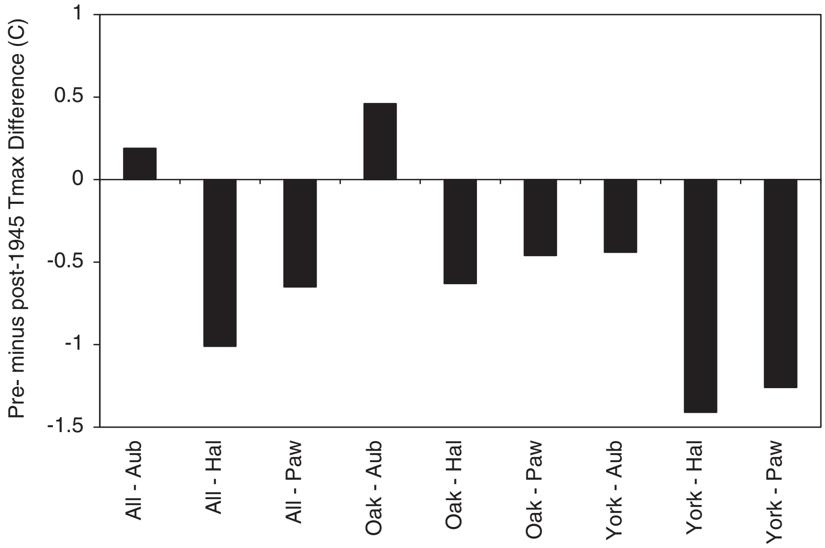

Figure 6. Cooling at irrigated locations in Nebraska, USA during the post-1945 period. Negative values show cooling. Alliance (All), Oakland (Oak), and York are irrigated locations while Halsey (Hal), Auburn (Aub), and Pawnee City (Paw) are non-irrigated locations (Source: Mahmood *et al.*, 2006).

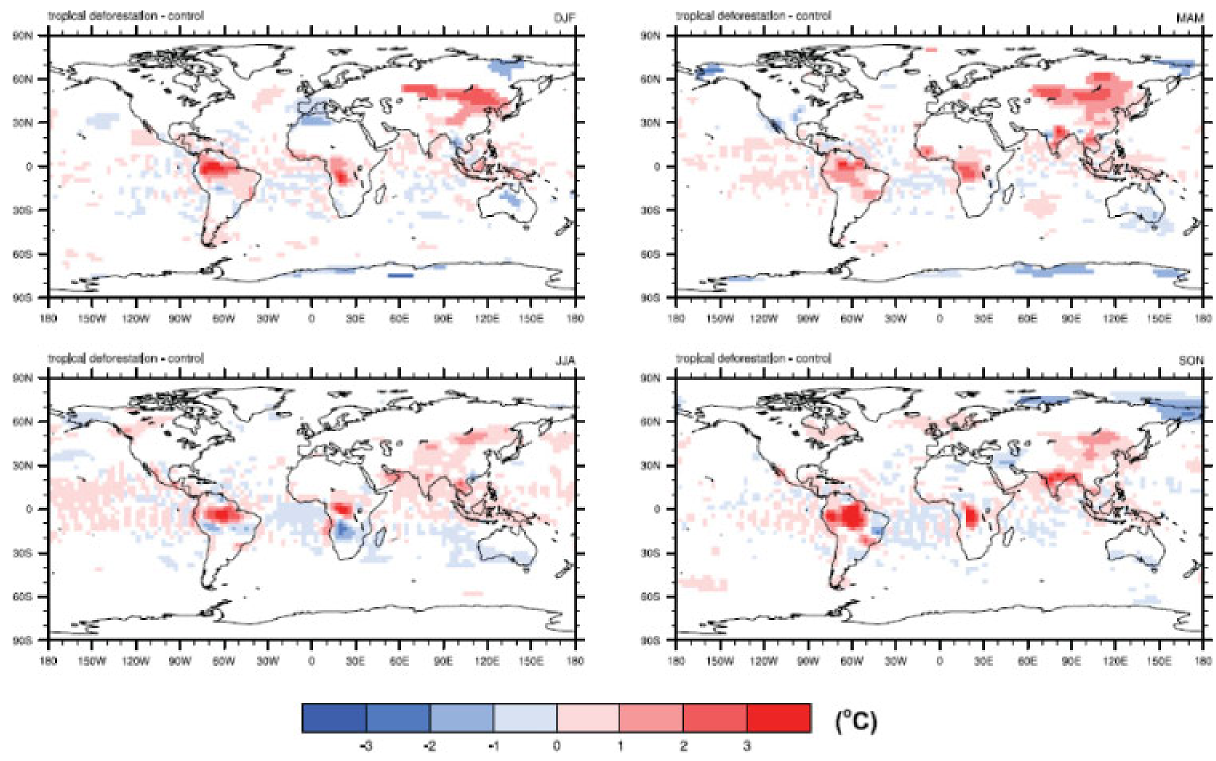

Figure 7. Tropical forest removal and its impacts on seasonal surface temperatures. These changes can also be seen over distant regions away from the location of deforestation (Source: Snyder, 2010).

links between global forests, LCC and climate change can be found in Bonan (2008b).

Despite the large area of deforestation globally, there is a recent positive trend in forest regrowth, afforestation and reforestation (Nagendra and Southworth, 2010). Little published literature is available about the effects of these processes on climate, although in general, observations and modelling studies agree that afforestation and reforestation decrease near-surface temperature due to increases in latent heat, LAI, roughness length, and rooting depth (Nosetto *et al.*, 2005; Pielke *et al.*, 2007; Strack *et al.*, 2008; Beltrán-Przekurat *et al.*, 2012).

LCC can also change the global average temperature. Various modelling studies provide ranges of estimated changes in global-scale temperature due to LCC. For example, Davin and Noblet-Ducoudré (2010) noted that global-scale deforestation may result in a 1 °C cooling of global mean temperature due to the resultant albedo change. This estimate exceeds the results of several previous model-based global-scale studies that reported a 0.03–0.82 °C cooling due to LCC (Betts, 2001; Claussen *et al.*, 2001; Matthews *et al.*, 2003, 2004; Brovkin *et al.*, 2006; Betts *et al.*, 2007; Davin *et al.*, 2007; Pongratz *et al.*, 2010). Findell *et al.* (2007), and Pitman *et al.* (2009) noted, respectively, a small amount of cooling in global average temperature, but disagreements among global models are a result of their variable sensitivity to LCC. On the other hand, Bounoua *et al.* (2002) found a 0.2 °C global surface warming if all forests and grasslands were replaced with croplands.

3.2.1. Summary

LCC impacts on temperature depend on the type of conversion. In particular, urbanization leads to significant warming while agriculture often leads to cooling. Agriculture-related cooling is further magnified if irrigation is introduced. On the other hand, tropical deforestation may lead to net warming, while in the mid-latitudes it may lead to cooling. Globally, deforestation may result in cooling. Also, afforestation may lead to low-latitude cooling and high-latitude warming.

Overall, the majority of observationally-based studies on agriculturally-driven LCC provided a fairly robust assessment of, and support to, the theoretical understanding of land surface-atmosphere interactions (e.g. Bonan, 2001; Kalnay and Cai, 2003; Christy *et al.*, 2006; Mahmood *et al.*, 2006; Bonfils *et al.*, 2008). Challenges associated with these studies include potential uncertainty due to shortcomings in observational data: station siting, exposure of instruments, maintenance, and lack of detailed metadata, among others. Some of the studies reviewed above used robust techniques to minimize these uncertainties. However, it is unclear whether it is possible to remove all of the biases.

A second approach to addressing LCC impacts summarized in the aforementioned studies includes observational analyses in support of hypothesized processes and mechanisms identified in regional models and established theories of land-surface atmosphere interactions (e.g. Adegoke *et al.*, 2003; Sen Roy *et al.*, 2007). Applications of biogeophysically based regional models provide an improved understanding of the causes of temperature changes and have helped refine the theories. However, many of these sensitivity studies – particularly on irrigation impacts – were based on limited atmospheric scenarios due to limited computational capabilities in the past. With improved computing resources, experiments can now be designed to include a broad range of atmospheric settings that investigate how LCC influences temperature.

3.3. Changes in atmospheric circulations and PBL

As has been described above, LCC alters the surface physical processes of albedo, net radiation, Bowen ratio, and momentum flux, and these are expressed in the climate variables of near-surface air temperature, humidity, wind speed, and soil moisture. LCC also affects the temperature, moisture and stability in the PBL that becomes evident, e.g. in convective cloud development and precipitation. In general, the top of the PBL is located closer to the ground at night over surfaces having low aerodynamic roughness (e.g. grasslands, crops) but is elevated due to daytime solar heating over rougher surfaces (forests and urban areas). Along and near steep horizontal gradients in LC types, the associated strong contrasts in albedo and convective fluxes can promote 'non-classical meso-scale circulations' (NCMCs) – so called because they resemble but are different in cause from the classical circulations of sea and land breezes – that may produce convective clouds and even precipitation in proximity to the LC boundaries (Segal *et al.*, 1988; Segal and Arritt, 1992). During daytime hours, an NCMC is characterized by vertical motion either along the boundary or displaced towards the surface having higher Bowen ratio values (i.e. strong sensible heat flux), but sinking air over the adjacent surface having lower Bowen ratio (i.e. where evaporation is greater). Accordingly, NCMCs become most evident between strongly contrasting LC types (e.g. Weaver *et al.*, 2002).

Because urban environment contains some of the above land surface characteristics, it modifies the PBL in particularly significant ways. Boundary layer changes include enhanced low-level convergence of air during the daytime ("country breeze"). The UHI is typically strongest during the nocturnal part of the diurnal cycle, but the UHI circulation is more evident during the daytime because of the urban–rural pressure gradient and vertical mixing during the daytime hours (Shreffler, 1978; Fujibe and Asai, 1984). This process explains why urban-forced convection and associated precipitation anomalies are not simply a night–early morning phenomenon. Vukovich and Dunn (1978) used a 3-D model to show that UHI intensity and PBL stability play dominant roles in UHI circulation. Huff and Vogel (1978) associated the urban circulation with increased sensible heat fluxes and surface roughness of the urban area.

Baik *et al.* (2007) and Han and Baik (2008) employed analytical and numerical models to show that PBL destabilization over the UHI leads to a region of enhanced vertical motion. They also argued that during the daytime, stability conditions were more conducive to stronger UHI-related circulations. In a model based assessment, Rozoff *et al.* (2003) found that non-linear interactions associated with friction, momentum drag, and heating could cause downwind convergence. Subsequently, Niyogi *et al.* (2006) showed that urban morphology affects both temperature and wind flow. Shem and Shepherd (2009) revealed that urban-induced convergence associated with urban circulation on the periphery of Atlanta's impervious land surface and increased sensible heat flux led to enhanced convection downwind of the city. Observational study by Shepherd *et al.* (2010a) and modelling experiments by, Carter *et al.* (2012), Lo *et al.* (2007), Yoshikado (1994), and Ohashi and Kida (2002) found similar results for Houston, Hong Kong, and cities in Japan.

In southwest Australia, analysis of radiosonde observations (the 2005–2007 Bunny Fence Experiment – BuFex) showed increased vigour of PBL development over native vegetation, leading to higher PBL heights during both winter and summer seasons, compared to agricultural areas. On average, the noontime PBL height was higher by ~260 m over the native vegetation during summertime, while during winter it was ~189 m (Nair *et al.*, 2011) (please see introductory sections for further explanation). Energy fluxes determined from aircraft show that the enhanced PBL development was driven by heat fluxes and were consistently higher over the native vegetation areas, with peak differences of $\sim 200\,\mathrm{W\,m^{-2}}$ and $\sim 100\,\mathrm{W\,m^{-2}}$ observed during the summer and winter seasons, respectively. Based on modelling studies, McPherson *et al.* (2004) and Mahmood *et al.* (2011) showed changes in meso-scale wind circulation, particularly, along the LC transitions, and PBL heights due to LCC in Oklahoma and Kentucky.

A number of modelling studies found expected changes in large-scale atmospheric circulations due to LCC (e.g. Zheng and Eltahir, 1998; Chase *et al.*, 2000; Sen *et al.*, 2004b; Sen *et al.*, 2004a; Feddema *et al.*, 2005; D'Almeida *et al.*, 2007; Abiodun *et al.*, 2008; Jonko *et al.*, 2010; Snyder, 2010; Lee *et al.*, 2011). For example, in a global modelling study, Chase *et al.* (2000) demonstrated that the modifications in tropical vegetation resulted in a northward-displaced westerly jet and reduction in its maximum intensity. Similarly, over the tropical Pacific basin, the strength of the low-level easterlies was also reduced. Feddema *et al.* (2005) found that LCC could lead to weakening of the Hadley circulations and large-scale changes in the strength and timing of Asian monsoon circulations. Recently, Lee *et al.* (2011) reported changes in the large-scale Asian monsoonal circulation due to irrigation. They noted that the cooling led to significant lowering of the tropospheric geopotential height over the irrigated regions, and also modified the upper level atmospheric circulation. These changes eventually led to weakening of the upper level Asian mid-latitude jet, through a series of feedback loops.

3.3.1. *Summary*

On meso- and regional-scales, different land cover types (e.g. trees versus crops, rainfed versus irrigated agriculture) and land cover conversions through time (e.g. deforestation, urbanization) alter the surface and near-surface climate variables of albedo, net radiation, the Bowen ratio of convective fluxes of sensible to latent heat, and aerodynamic roughness and momentum flux. These alterations are expressed as increased spatial variability of near-surface air temperature, atmospheric humidity, and PBL characteristics of depth and stability. Accordingly, sea breeze-like meso-scale circulations within the PBL (i.e. NCMCs) can develop along and near the boundaries or transition zones of LC types (urban–rural interface, dryland-irrigated agriculture), and potentially promoting preferred areas of convective cloud formation and precipitation. Despite the progress in our understanding of these processes, the role of urbanization on meso-, and potentially regional-scale atmospheric circulation needs significant additional research over the coming years. This assertion also applies to other LCC-driven land-surface boundaries.

3.4. Teleconnections

The above assessment shows that biogeophysical impacts of LCC on local and regional-scale are significant, undeniable and discernible. Scientific research has also indicated possible teleconnections between regional LCC and climate over remote areas (e.g. Hasler *et al.*, 2009; Snyder, 2010). However, impacts of LCC on global climate and its variations are still under investigation and not fully understood (Pielke *et al.*, 2011). In addition, the question of whether LCC global impacts could be as prominent as El Niño or La Niña, or greenhouse gases, remain to be fully explored using adequate land surface representations in global models. It should be emphasized that El Niño and La Niña are large-scale coupled ocean-atmospheric oscillations, and are dynamic and cyclical over inter-annual and multi-decadal time-scales, while LCC becomes relatively 'static' after completion of the change process. LCC impacts behave more like a trend similar to greenhouse gas effects, but with great regional variability.

The lack of a persistent global climate response to LCC is partly because of the opposing and offsetting signals of local and regional impacts, and the fact that global averaging cancels and minimizes these climatic responses (e.g. Feddema *et al.*, 2005; Kvalevåg *et al.* 2010; Lawrence and Chase, 2010). For example, the modelling study of Claussen *et al.* (2001) found that low-latitude deforestation leads to regional warming and extratropical cooling via its effects on the energy and water cycles, as well as global average warming due to impacts on the carbon cycle. On the other hand, high-latitude deforestation showed a cooling effect, dominated by impacts on the surface energy balance. Modelling studies by Snyder *et al.* (2004) and Davin and Noblet-Ducoudré (2010) corroborate these results, finding cooling for both boreal and temperate deforestation, and warming as a result of tropical deforestation. However, afforestation appears to produce low-latitude cooling and high-latitude warming (Claussen *et al.*, 2001; Bala *et al.*, 2007). Despite strong regional effects, the global response to large-scale deforestation has been shown to be a slight net cooling in model simulations (Claussen *et al.*, 2001; Bala *et al.*, 2007).

Similarly, Sacks *et al.* (2009) suggested that the impacts of irrigation were significant on the regional-scales but global-scale averaged impacts were not noticeable. However, the modelling study by Puma and Cook (2010) found that regional cooling effects were already significant over southern and eastern Asia early in the 20th century, but became significant across the middle-latitude croplands after the mid-20th century. They noted that Asia and parts of North America experienced winter season warming during the last part of the 20th century due to increased irrigation. Puma and Cook (2010) also found a weakening of the Indian monsoon. Their results suggest a significant lowering of temperature, negative temperature trends, and increased precipitation in the tropics and the Northern Hemisphere middle-latitudes starting around the 1950s and thus, irrigation is an important component of LCC and the future global climate.

A number of modelling studies have found teleconnections between regional-scale LCC and climates of distant regions (Chase *et al.*, 2000, 2001; Gedney and Valdes, 2000; Zhao *et al.*, 2001; Werth and Avissar, 2002). Snyder *et al.* (2004) conducted a detailed global modelling study to investigate the impacts of removal of each of the six biomes. They found significant changes, not only in global average temperature and precipitation, but also in responses of these variables in regions away from the LCC. For example, it was found that tropical deforestation may result in up to a 2.5 mm d^{-1} reduction in precipitation over both oceanic and land areas distant from regions of LCC. Air temperature in remote regions also showed similar changes (Snyder *et al.*, 2004; Snyder, 2010) (Figure 7). In several subsequent modelling experiments Cui *et al.* (2006) and Hasler *et al.* (2009) found similar teleconnections between LCC and the climate of remote areas. Cui *et al.* (2006) noted that LCC in Tibet impacts East Asian atmospheric circulation and monsoon precipitation while Takata *et al.* (2009) also found significant alterations in the Asian monsoon from landscape change. The pattern and intensity of the Asian monsoon circulation impact circulations elsewhere in both the northern and southern hemispheres. Recently, Snyder (2010) further investigated impacts of LCC, reporting strong relationships between tropical deforestation and the Northern Hemisphere atmospheric circulation changes. This model based study indicates, e.g. that removal of tropical forest weakens deep convective activity and eventually impacts the northern extratropics by modifying the strength of the westerlies. Moreover, LCC in the tropics may change European storm tracks and shift the Ferrel cell northward. Amazon deforestation may modulate remote tropical ocean and climate variability (Voldoire and Royer, 2005; Schneider *et al.*, 2006; Nobre *et al.*, 2009), while the deforestation signal on weather patterns may vary in strength with the phase of El Niño (Da Silva *et al.*, 2008). Nobre *et al.* (2009), in a modelling study, found that the replacement of Amazonian tropical forest with grassland produces an ENSO-like response over the tropical Pacific Ocean, which further reduces rainfall over Amazonia. Sen *et al.* (2004b) also reported distant responses of deforestation over Indochina, including weakening of the monsoon flow over the Tibetan Plateau and eastern China.

As Findell *et al.* (2006) noted, that, it would be difficult to differentiate the extratropical response to LCC from natural climate variability. Voldoire and Royer (2005) also reported weak remote impacts of tropical deforestation. Based on a detailed model intercomparison study, Pitman *et al.* (2009) found no common remote responses to LCC. However, they noted, that this could be a function of the various model parameterizations, the use of prescribed fixed sea surface temperature and inclusion of a relatively small tropical LCC signal. It has been demonstrated that tropical LCC would produce the most significant global teleconnection response (e.g. Snyder, 2010). In addition, we note that Pitman *et al.* (2009) have used more muted global LCC (1870 *vs* current) than the other sensitivity studies (e.g. Snyder *et al.*, 2004; Snyder, 2010).

A key question is whether these drastic LCCs will occur in the future. On the basis of the past history of human modification of the land, these cannot be ruled-out. Current estimates of land cover change in the coming decades indicate a continuation from the last century, particularly in developing countries with large population growth, but also in developed countries as different land uses are implemented (e.g. production of biofuels). Moreover, such drastic changes demonstrate teleconnections between LCC of one region and the climate of distant regions. Therefore, it cannot be concluded that the climate of the distant regions will not respond to LCC of another region.

4. Incompletely understood issues

Despite progress over the recent decades, currently there remains a lack of comprehensive understanding of irrigation impacts on the regional-scale atmosphere and climate (e.g. via precipitation recycling). Bagley *et al.* (2012) show the potential impact on regional atmospheric water budgets of evaporated water from major croplands, hinting at the potential impacts of LCC and irrigation. A modelling study by Lobell *et al.* (2009) demonstrates varying regional response of temperature due to irrigation. These could be linked, in addition of model uncertainty and experimental design, to any or all of the following factors: varying levels of irrigation adoption and application, regional extent of irrigation, regional atmospheric feedback loops, and interactions between regional and large-scale circulations. In the broader sense, Keys *et al.* (2012) show the potential vulnerability of different regions to local and remote disruptions to evapotranspiration via processes like LCC or irrigation that may alter the atmospheric water supply to an area using the concept of 'precipitation-sheds'.

4.1. Deforestation

Deforestation rates vary by country and fluctuate over time in reaction to economic and political pressures. For example, the rate has increased within Latin American countries from 1.8% per year during the 1990s to over 3.2% per year in the most recent decade (FAO, 2011). These changes are dynamic, involving multiple land use pathways often leading to some form of forest re-growth, which is an important trend in Latin America (Grau and Aide, 2008). However, re-burning is often practiced to maintain cleared lands, especially for grazing (Fisch *et al.*, 1994). Precise knowledge of transition types of LCCs is critical in areas with dynamic agricultural frontier expansion.

Sampaio *et al.* (2007) suggested a tipping point of around 40% deforestation for the Amazon, after which climate impacts accelerate and a new equilibrium of reduced forest is reached. These effects are stronger for the transition to crops (soybean) than to pasture (Costa *et al.*, 2007). In their early modelling studies, Nobre *et al.* (1991) first hinted at the possibility of multiple equilibria in the Amazon Basin. Other factors may reinforce the forest retreat, including climate change (Salazar *et al.*, 2007) and the effect of natural fires from lightning (Hirota *et al.*, 2010). Tropical forests provide a number of biogeophysical feedbacks to the global climate system, and tropical deforestation works against mitigation of global climate change (Bonan, 2008b). However, the CO_2 fertilization effect could encourage tropical forest growth (Lapola *et al.*, 2009; Salazar and Nobre, 2010).

4.2. Benefits of reforestation?

Another important unknown issue is the capacity of reforestation to mitigate the biogeophysical climate impacts of LCC at a regional scale and which spatial configurations of vegetation might help enhance recycling of water vapour to the atmosphere through the regulation of energy fluxes, wind and surface water availability. Latitude-specific deforestation modelling experiments conducted by Bala *et al.* (2007) indicate clearly that reforestation projects in tropical regions would be beneficial in mitigating global-scale warming. However, it would be counterproductive if implemented at high latitudes and would offer only marginal benefits in temperate regions. The evidence assembled in Bala *et al.* (2007) demonstrates that deforestation in tropical and sub-tropical regions can have a significant warming and drying effect on regional climate, with teleconnections to regions remote from where the deforestation occurs. Large-scale reforestation has the potential to ameliorate regional climate changes associated with deforestation while providing other ecological services such as biodiversity, clean air and water. However, we currently do not know the extent to which such actions will modify temperature and rainfall patterns directly (McAlpine *et al.*, 2009). A related question thus is: How much vegetation is required and where should it be located? Should vegetation be configured in large blocks or in linear strips/vegetation bands, which are more amenable to integrating the production functions of landscapes (Ryan *et al.*, 2010)?

4.3. Coupling ecosystem dynamics with climate feedbacks

Most research to date on the climate impacts of LCC has focused on anthropogenic modification. However, terrestrial ecosystems and the climate system are closely coupled, with multiple interactions and feedbacks occurring across a range of scales (e.g. Chapin *et al.*, 2008). Extreme climatic events such as heatwaves, droughts, and floods can have disproportionate effects on ecosystems relative to the scale at which they occur. The timing of these events has a critical influence on their impact. For example, synergisms between heatwave and drought aggravate the negative effect on plant growth and function (De Boeck *et al.*, 2011). There is growing evidence of committed ecosystem changes due to climate change, with predicted northern expansion of boreal forests with lower net primary productivity and increased risk of forest die-off in the Amazon (Jones *et al.*, 2009). A recent example is the widespread dieback of Amazon forest due to severe drought in 2005 (Phillips *et al.*, 2009). Drought-induced forest die-off in the region may increase the biogeophysical climate impacts of deforestation, and constitutes a large uncertainty in regional climate–ecosystem interactions, and also carbon-cycle feedbacks within global climate (McAlpine *et al.*, 2010). A recent special report on extreme events by Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) predicts that droughts will intensify in some regions such as the Mediterranean, central North America, South Africa and Australia (IPCC, 2012). This possibility highlights the importance of coupling dynamic vegetation models with regional and global climate models when investigating the biogeophysical feedbacks of LCC on the climate system.

In the context of the above discussion and the emergence of a clearer picture of regional-scale climatic response to LCC and a complex global-scale response, we propose a series of tasks. These are presented in the following subsections.

5. Recommendations

5.1. Broadening the scope of IPCC

An important lesson to be drawn from this article is the need to broaden the current global climate change agenda to recognize that climate change results from multiple forcings, and that LCC must be included in global and regional strategies to effectively mitigate climate change (Feddema *et al.*, 2005; NRC, 2005). The forthcoming IPCC's Fifth Assessment currently lacks a comprehensive evaluation of the relative impact of biogeophysical feedbacks of LCC on regional climate. Mahmood *et al.* (2010) argues that the development of suitable regional policies to adapt to the impacts of climate change, including LCC effects, must be assessed in detail as part of the IPCC Fifth Assessment, in order for them to be scientifically complete. Current risk assessments such as the special report on extreme events (IPCC, 2012) fail to account for these feedbacks. A coordinated research effort is required to address this problem, as the biogeophysical LCC forcing of climate may, in some regions, be of similar magnitude or larger than that of greenhouse gas-induced climate change (Bonan, 2008b; Avila *et al.*, 2012).

5.2. Detection of climatic impacts of LCC with in situ measurements

A number of observational platforms should be used for better detection of climate impacts of LCC. These include *in situ* observing networks and satellites. High quality *in situ* measurements can play an important role in detecting the signals of LCC impacts. Note that the improved observational data are also necessary to fully drive the models at the resolution necessary for more accurate simulations of LCC-driven atmospheric processes. Urban micronets, such as the one in Oklahoma City (Basara *et al.*, 2009), need to be established. This type of network could be further expanded to study the role of urban morphology, shape, and form on precipitation (particularly winter precipitation), urban cloud climatologies, synergistic mechanisms and on when they are most dominant (e.g. diurnally, seasonally, and or as function of meteorological regime). High quality mesonets such as those in Oklahoma, Kentucky, Nebraska, and Delaware should also be used and expanded to other regions. Some of these mesonets could be located in regions experiencing significant LCC or where climate response could be significant (e.g. the Amazon, African tropical forests, and Boreal forests). Analysis of long-term data collected by the mesonets, and the knowledge of LCC in the vicinity, allow for linking LCC to its impacts on climate. The US Regional Climate Reference Network (USRCRN) could be used along with these mesonets to detect regional LCC-forced climate signals. The US Climate Reference Network (USCRN) can also be a useful observation platform to help in this detection.

In addition to its well-known effect on air temperature, LCC also adversely affects the measurement of precipitation. When averaged across the entire globe and for all seasons, the underestimation bias associated with precipitation measurement results in a decrease of about 8% due to the wind, 2% to wetting losses on the internal walls of the gauge and on the collector during its emptying, and 1% resulting from evaporation losses of storage gauges (Legates, 1987; Legates and Willmott, 1990). LCC can affect these biases, thereby introducing artificial trends or masking real trends in the precipitation time-series (Legates, 1995). In particular, the growth of trees and urban sprawl near a precipitation gauge can alter the wind speed and/or temperature (thereby affecting the distribution of solid versus liquid precipitation) across the gauge orifice, which systematically decreases the bias in precipitation gauge measurement. This bias decrease results in an artificial increase in precipitation that may be indistinguishable from the true precipitation amounts. In particular, checks for discontinuities in the data are not likely to identify such changes in the mean bias as they are slow, gradual and indistinguishable from true precipitation signals. As a result, when attempting to detect LCC impacts on observed precipitation, the data should be carefully evaluated for such biases.

Data from global networks such as FluxNet should also be used to detect responses of regional climate to LCC. These networks provide rich data sets that include, in addition to standard meteorological measurements, energy, water and carbon flux observations. Currently, the length of the time series for some stations within these networks is nearly two decades. As a result, they provide an excellent opportunity to assess the potential response of the regional atmosphere linked to LCC.

The large-scale adoption of irrigation in many parts of the world and its reported impacts on weather and climate, means that extensive field experiments should be undertaken to better understand the role of irrigation in the structure, evolution and modulation of the PBL at meso- and regional scales. These efforts may also be carried out in the context of severe weather impacts, and should include modelling activities to complement field campaigns and better identify the associated physical processes.

5.3. Detection of LCC Using Satellite Data

LC data collected by satellites have been explicitly used over the last several decades to monitor changes (Townshend *et al.*, 1991; DeFries and Townshend, 1994) and to establish links between LCC and the climate response (Rabin *et al.*, 1990; Carleton *et al.*, 1994; McPherson *et al.*, 2004; Jin *et al.*, 2007). Normalized Difference Vegetation Index (NDVI) and similar indices derived from optical remote sensing data have been widely used in LCC detection and are expected to continue to be used for the foreseeable future. In addition, passive microwave sensors, such as Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) offer valuable land cover information over the relatively long term, based on the Microwave Polarization Difference Temperature (MPDT) by which the leaf water content can be derived (e.g. Justice *et al.*, 1989). In addition to leaf water content, the MPDT is also related to soil moisture, surface roughness, and canopy structure. SMMR and SSM/I also allow for the characterization of land cover categories (Townshend *et al.*, 1989; Neale *et al.*, 1990). Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), a successor in technology to SMMR and SSM/I, provides vegetation water content and surface soil moisture in addition to surface temperature (Njoku, 1999; Du, 2012). AMSR-E also provides derived indices such as a microwave vegetation index (MVI) and global vegetation/roughness maps (Shi *et al.*, 2008). Vegetation conditions and soil moisture can also be estimated from the European Space Agency (ESA) L-band Soil Moisture and Ocean Salinity (SMOS) mission (Kerr *et al.*, 2010), and NASA's planned Soil Moisture Active Passive (SMAP) mission (Entekhabi *et al.*, 2010). Active microwave sensors, such as the European Remote-Sensing Satellite (ERS) scatterometer, provide land cover classification in addition to meso-scale surface geophysical parameters such as vegetation cover, surface roughness, and surface soil-moisture content. Polarimetric and interferometric (PolInSAR), multi-angle optical remote sensing, and Light Detection And Ranging (LiDAR) should also continue to be used for measurements of the vertical structure of vegetation (e.g. Lefsky *et al.*, 2002; Harding and Carabajal, 2005; Lefsky *et al.*, 2005; Lefsky *et al.*, 2007).

Indirectly, satellites have detected the hydrologic fingerprint of changing land use practices. Rodell *et al.* (2009) used a decade's worth of data from the Gravity Recovery And Climate Experiment (GRACE) to detect a significant depletion of groundwater over northwestern India related to greatly expanded irrigation-fed agriculture in the region. Similar GRACE assessments of groundwater depletion by agriculture have been performed for the Sacramento and San Joaquin valleys of California (Famiglietti *et al.*, 2011).

5.4. Modelling

The previously described modelling studies provide important clues as to how LCC impacts climate. They lend further support for additional research and improvement in modelling, including more realistic representations of the land surface, as highlighted in the model inter-comparison study by Pitman *et al.* (2009). These authors have noted that the sources of some limitations and uncertainties in their experiments originated from '*lack of consistency in*: *1) the implementation of LCC despite agreed maps of agricultural land*, *2) the representation of crop phenology*, *3) the parameterization of albedo*, *and 4) the representation of evapotranspiration for different land cover types*' (p. 1). Future modelling work should consider addressing these challenges for improved assessment of the climatic impacts of LCC.

Both Puma and Cook (2010) and Gordon *et al.* (2005) demonstrated the importance of irrigation as LCC and its impacts on global climate. Thus, in addition to the regional-scale, the role of irrigation in global climate should be further investigated. Large-scale global climate model-based studies should be conducted to improve understanding of physical processes and to quantify the climatic impacts of irrigation.

More accurate vegetation and management data are also needed if the goal is to continually improve the simulations focusing on climatic impacts of LCC. In the recent decades, a number of global and regional data sets for LCC (Ramankutty and Foley, 1999; Goldewijk, 2001; Waisenan and Bliss, 2002; Brown *et al.*, 2005; Pongratz *et al.*, 2008; Ramankutty *et al.*, 2008; Steyaert and Knox, 2008), fertilizer application (Potter *et al.*, 2010) and irrigation (Siebert *et al.*, 2005; Wisser *et al.*, 2010; http://www.iwmigiam.org/, accessed in July 2012) have been produced. Despite considerable progress, there is still significant room for improving the accuracy of these data sets.

Interactions among scales need to be assessed within the current modelling framework. Steyaert and Knox (2008) introduced a new analysis of LC in the eastern United States for several periods since 1650. Their data set is unique in that they present values of surface properties in the parameter format used by the modelling community, and at a reasonably fine-scale spatial resolution. They have found, when examining the large temporal changes in LC (on a fine spatial scale) for this region, that LCCs played a major role in local and regional climates and in attributing observed temperature trends. The other examples could be how meso- and regional-scale climate, modified by the LCC, interacts with large-scale climate.

The scientific community needs a more complete and coordinated investigation addressing LCC and teleconnections. In our opinion, we should build upon previous studies (e.g. Voldoire and Royer, 2004, 2005; Pitman *et al.*, 2009; Snyder, 2010) and conduct more robust and realistic multi-model global-scale simulations and analyses. This line of research should include the forcing of LCCs on global climate, in addition to their interactions with the large-scale coupled ocean–atmosphere oscillations.

Model applications are needed to examine LCC impacts on more extreme weather and climate conditions (e.g. severe thunderstorms, flash floods, floods, drought, and seasonal wetness and dryness). Detailed studies of meso- and synoptic-scale interactions of urbanization with climate are also needed. This is because urbanization represents one of the most intense and multifaceted alterations of landscape for its comparable spatial scale. Some of the challenges for these studies have been the absence of land use data to properly characterize urban physical properties and their representation in models. Recently, Oleson *et al.* (2008a, 2008b, 2010) and Jackson *et al.* (2010) have made some important progress to this end. However, additional research needs to be conducted to overcome challenges related to improved characterization and parameterization of urban surfaces so that the urban meso- and synoptic-scale interactions can be modelled realistically.

The review and synthesis comprising this article have demonstrated that LCC plays an important and spatio-temporally varied role in modifying climate. We conclude that climate change metrics of LCC should become part of any climate assessment. In addition, there are other metrics to be considered such as the magnitude of moist enthalpy changes, magnitude of the spatial redistribution of land surface latent and sensible heating (i.e. Bowen ratio), the magnitude of the spatial redistribution of precipitation and moisture convergence, and the normalized gradient of regional radiative heating changes (Mahmood *et al.*, 2010). In summary, humans are changing the face of the planet at an accelerated rate and the findings from LCC studies for all spatial scales should be incorporated into developing climate change and variability metrics that address impacts on atmospheric circulations, hydrologic cycles, and water resources.

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References

Abiodun BJ, Pal JS, Afiesimama AE, Gutowski WJ, Adedoyin A. 2008. Simulation of West African monsoon using RegCM3. Part II: impacts of deforestation and desertification. *Theoretical and Applied Climatology* **93**: 245–261.

Adegoke JO, Pielke RA Sr, Eastman J, Mahmood R, Hubbard KG. 2003. Impact of irrigation on midsummer surface fluxes and temperature under dry synoptic conditions: a regional atmospheric model study of the U.S. High Plains. *Monthly Weather Review* **131**: 556–564.

Adegoke JO, Pielke RA Sr, Carleton AM. 2007. Observational and modeling studies of the impact of agriculture-related land use change on climate in the central U.S. *Agricultural and Forest Meteorology* **142**: 203–215.

Allard J, Carleton AM. 2010. Mesoscale associations between midwest land surface properties and convective cloud development in the warm season. *Physical Geography* **31**: 107–136.

Anthes RA. 1984. Enhancement of convective precipitation by mesoscale variations in vegetative covering in semiarid regions. *Journal of Climate and Applied Meteorology* **23**: 541–554.

Aoyagi T, Kayaba N, Seino N. 2012. Numerical simulation of the surface air temperature change caused by increases of urban area, anthropogenic heat, and building aspect ratio in the Kanto-Koshin area. *Journal of the Meteorological Society of Japan* **90B**: 11–31.

Arnfield AJ. 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology* **23**: 1–26.

Ashley W, Bentley M, Stallins T. 2012. Urbaninduced thunderstorm modification in the Southeast United States. *Climatic Change* **113**: 481–498. DOI:10.1007/s10584-011-0324-1

Avila FB, Pitman AJ, Donat MG, Alexander LV, Abramowitz G. 2012. Climate model simulated changes in temperature extremes due to land cover change. *Journal of Geophysical Research* **117**: D04108. DOI: 10.1029/2011JD016382

Avissar R, Werth D. 2005. Global hydroclimatological teleconnections resulting from tropical deforestation. *Journal of Hydrometeorology* **6**: 134–145.

Bagley JE, Desai AR, Dirmeyer PA, Foley JA. 2012. Effects of land cover change on precipitation and crop yield in the world's breadbaskets. *Environmental Research Letters* **7**: 014009. DOI: 10.1088/1748-9326/7/1/014009

Baik JJ, Kim YH, Kim JJ, Han JY. 2007. Effects of boundary-layer stability on urban heat island-induced circulation. *Theoretical and Applied Climatology* **89**(1–2): 73–81.

Bala G, Caldeira K, Wickett M, Phillips TJ, Lobell DB, Delire C, Mirin A. 2007. Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences of the United States of America* **104**: 6550–6555.

Balling RC Jr. 1988. The climatic impacts of a Sonoran vegetation discontinuity. *Climatic Change* **13**: 99–109.

Balling RC Jr, Klopatek JM, Hilderbrandt ML, Moritz CK, Watts CJ. 1998. Impacts of land degradation on historical temperature records from the Sonoran desert. *Climatic Change* **40**(669): 681.

Barnston A, Schickedanz PT. 1984. The effect of irrigation on warm season precipitation in the southern Great Plains. *Journal of Climate and Applied Meteorology* **23**: 865–888.

Basara JB, Illston B, Winning TE et al. 2009. Evaluation of rainfall measurements from the WXT510 Sensor for use in the Oklahoma City Micronet. *The Open Atmospheric Science Journal* **3**: 39–45.

Beltrán-Przekurat A, Pielke RA Sr, Eastman JL, Coughenour MB. 2012. Modeling the effects of land-use/land-cover changes on the near-surface atmosphere in southern South America. *International Journal of Climatology* **32**: 1206–1225. DOI: 10.1002/joc.2346

Bentley ML, Stallins JA. 2008. Synoptic evolution of Midwestern US extreme dew point events. *International Journal of Climatology* **28**: 1213–1225.

Berbet ML, Costa MH. 2003. Climate change after tropical deforestation: seasonal variability of surface albedo and its effects on precipitation change. *Journal of Climate* **16**: 2099–2104.

Betts RA. 2001. Biogeophysical impacts of land use on present-day climate: near-surface temperature change and radiative forcing. *Atmospheric Science Letters* **2**: 39–51. DOI: 10.1006/asle.2001.0023

Betts AK, Desjardins RL, Worth D. 2007. Impact of agriculture, forest and cloud feedback on the surface energy budget in BOREAS. *Agricultural and Forest Meteorology* **142**: 156–169.

Biggs TW, Scott CA, Gaur A, Venot JP, Chase T, Lee E. 2008. Impacts of irrigation and anthropogenic aerosols on the water balance, heat fluxes, and surface temperature in a river basin. *Water Resources Research* **44**: W12415. DOI: 10.1029/2008WR006847

Bonan GB. 1997. Effects of land use on the climate of the United States. *Climate Change* **37**: 449–486.

Bonan GB. 2001. Observational evidence for reduction of daily maximum temperature by croplands in the Midwest United States. *Journal of Climate* **14**: 2430–2442.

Bonan GB. 2008a. *Ecological Climatology: Concepts and Applications*. Cambridge University Press: Cambridge; 678.

Bonan GB. 2008b. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* **320**: 1444–1449.

Bonfils C, Lobell D. 2007. Empirical evidence for a recent slowdown in irrigation induced cooling. *Proceedings of the National Academy of Sciences of the United States of America* **104**: 13582–13587.

Bonfils C, Duffy PB, Santer BD, Wigley TML, Lobell DB, Phillips TJ, Doutriaux C. 2008. Identification of external influences on temperatures in California. *Climatic Change* **87**(Suppl. 1): S43–S55.

Bornstein R, Lin Q. 2000. Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. *Atmospheric Environment* **34**: 507–516.

Bounoua L, DeFries RS, Collatz GJ, Sellers PJ, Khan H. 2002. Effects of land cover conversion on surface climate. *Climatic Change* **52**: 29–64.

Bowen IS. 1926. The ratio of heat losses by conduction and by evaporation from any water surface. *Physical Review* **27**: 779–787.

Brovkin V, Sitch S, Werner VB, Claussen M, Bauer E, Cramer W. 2004. Role of land cover changes for atmospheric CO_2 increase and climate change during the last 150 years. *Global Change Biology* **10**: 1253–1266. DOI: 10.1111/j.1365-2486.2004.00812.x

Brovkin V, Claussen M, Driesschaert E, Fichefet T, Kicklighter D, Loutre MF, Matthews HD, Ramankutty N, Schaeffer M, Sokolov A. 2006. Biogeophysical effects of historical land cover changes simulated by six Earth system models of intermediate complexity. *Climate Dynamics* **26**: 587–600.

Brown DG, Johnson KM, Loveland TR, Theobald DM. 2005. Rural land use change in the conterminous U.S., 1950–2000. *Ecological Applications* **15**: 1851–1863.

Caldwell P, Sun G, McNulty S, Cohen E, Myers JM. 2012. Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US. *Hydrology and Earth System Science* **16**: 2839–2857.

Campra P, Garcia M, Canton Y, Palacios-Orueta P-OA. 2008. Surface temperature cooling trends and negative radiative forcing due to land use change toward greenhouse farming in southeastern Spain. *Journal of Geophysical Research* **113**: D18109. DOI: 10.1029/2008JD009912

Carleton AM, Jelinski D, Travis D, Arnold D, Brinegar R, Easterling D. 1994. Climatic-scale vegetation – cloud interactions during drought using satellite data. *International Journal of Climatology* **14**: 593–623.

Carleton AM, Adegoke JO, Allard J, Arnold DL, Travis DJ. 2001. Summer season land cover-convective cloud associations for the Midwest U.S. "Corn Belt". *Geophysical Research Letters* **28**: 1679–1682.

Carleton AM, Arnold DL, Travis DJ, Curran S, Adegoke JO. 2008a. Synoptic circulation and land surface influences on convection in the Midwest U.S. "Corn Belt" during the summers of 1999 and 2000a. Part I: composite synoptic environments. *Journal of Climate* **21**: 3389–3414.

Carleton AM, Travis DJ, Adegoke JO, Arnold DL, Curran S. 2008b. Synoptic circulation and land surface influences on convection in the Midwest U.S. "Corn Belt" during the summers of 1999 and 2000b. Part II: role of vegetation boundaries. *Journal of Climate* **21**: 3617–3641.

Carter WM, Shepherd JM, Burian S, Jeyachandran I. 2012. Integration of lidar data into a coupled mesoscale-land surface model: a theoretical assessment of sensitivity of urban-coastal mesoscale circulations to urban canopy. *Journal of Atmospheric and Oceanic Technology* **29**: 328–346.

Chagnon FJF, Bras RL, Wang J. 2004. Climatic shift in patterns of shallow clouds over the Amazon. *Geophysical Research Letters* **31**: L24212. DOI: 10.1029/2004GL021188

Changnon SA, Semonin RG, Auer AH, Braham RR, Hales J. 1981. METROMEX: a review and summary, Meteorological Monographs No. 40, American Meteorological Society, 181 pp.

Chapin FS III, Randerson JT, McGuire AD, Foley JA, Field CB. 2008. Changing feedbacks in the climate–biosphere system. *Frontiers in Ecology and the Environment* **6**: 313–320.

Chase TN, Pielke RA Sr, Kittel TGF, Nemani RR, Running SW. 2000. Simulated impacts of historical land cover changes on global climate in northern winter. *Climate Dynamics* **16**: 93–105.

Chase TN, Pielke RA Sr, Kittel TGF, Zhao M, Pitman AJ, Running SW, Nemani RR. 2001. Relative climatic effects of landcover change and elevated carbon dioxide combined with aerosols: a comparison of model results and observations. *Journal of Geophysical Research* **106**(D23): 31,685–31,691.

Christy JR, Norris WB, Redmond K, Gallo KP. 2006. Methodology and results of calculating central California surface temperature trends: evidence of human-induced climate change? *Journal of Climate* **19**: 548–563.

Claussen M, Brovkin V, Ganopolski A. 2001. Biogeophysical versus biogeochemical feedbacks of large-scale land cover change. *Geophysical Research Letters* **28**: 1011–1014.

Cook BI, Puma MJ, Krakauer NY. 2011. Irrigation induced surface cooling in the context of modern and increased greenhouse gas forcing. *Climate Dynamics* **37**: 1587–1600.

Costa MH, Yanagi SNM, Souza PJOP, Ribeiro A, Rocha EJP. 2007. Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. *Geophysical Research Letters* **34**: L07706. DOI: 10.1029/2007GL029271

Cotton WR, Pielke RA Sr. 2007. *Human Impacts on Weather and Climate*. Cambridge University Press: New York; 308.

Cui X, Graf H-F, Langmann B, Chen W, Huang R. 2006. Climate impacts of anthropogenic land use changes on the Tibetan Plateau. *Global and Planetary Change* **54**: 33–56.

D'Almeida C, Vörösmarty CJ, Hurtt GC, Marengo JA, Dingman SL, Keim BD. 2007. The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. *International Journal of Climatology* **27**: 633–647.

Da Silva RR, Werth D, Avissar R. 2008. Regional impacts of future land-cover changes on the Amazon basin wet-season climate. *Journal of Climate* **21**: 1153–1170.

Davin EL, Noblet-Ducoudré N. 2010. Climatic impact of global-scale deforestation: radiative versus nonradiative processes. *Journal of Climate* **23**: 97–112.

Davin EL, Noblet-Ducoudré N, Friedlingstein P. 2007. Impact of land cover change on surface climate: relevance of the radiative forcing concept. *Geophysical Research Letters* **34**: L13702. DOI: 10.1029/2007GL029678

De Boeck HJ, Dreesen FE, Janssens IA, Nijs I. 2011. Whole-system responses of experimental plant communities to climate extremes imposed in different seasons. *New Phytologist* **189**: 806–817.

DeAngelis A, Dominguez F, Fan Y, Robock A, Kustu MD, Robinson D. 2010. Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States. *Journal of Geophysical Research* **115**: D15115. DOI: 10.1029/2010JD013892

DeFries RS, Townshend JRG. 1994. NDVI derived classifications at a global scale. *International Journal of Remote Sensing* **17**: 3567–3686.

DeFries RS, Bounoua L, Collatz GJ. 2002. Human modification of the landscape and surface climate in the next fifty years. *Global Change Biology* **8**: 438–458.

DeFries RS, Foley JA, Asner GP. 2004. Land-use choices: balancing human needs and ecosystem function. *Frontiers in Ecology and the Environment* **2**: 249–257.

Deo RC, Syktus JS, McAlpine CA, Lawrence PJ, McGowan HA, Phinn SR. 2009. Impact of historical land cover change on daily indices of climate extremes including droughts in eastern Australia. *Geophysical Research Letters* **36**: L08705. DOI: 10.1029/2009GL037666

Dirmeyer PA. 1994. Vegetation as a feedback mechanism in mid-latitude drought. *Journal of Climate* **7**: 1463–1483.

Dirmeyer PA, Shukla J. 1996. The effect on regional and global climate of expansion of the world's deserts. *Quarterly Journal of the Royal Meteorological Society* **122**: 451–482.

Douglas EM, Niyogi D, Frolking S, Yeluripati JB, Pielke RA Sr, Vörösmarty CJ, Mohanty UC. 2006. Changes in moisture and energy fluxes due to agricultural land use and irrigation in the Indian Monsoon Belt. *Geophysical Research Letters* **33**. DOI:10.1029/2006GL026550

Douglas EM, Beltrán-Przekurat A, Niyogi D, Pielke RA Sr, Vörösmarty CJ. 2009. The impact of agricultural intensification and irrigation on land–atmosphere interactions and Indian monsoon precipitation – a mesoscale modeling perspective. *Global and Planetary Change* **67**: 117–128.

Du J. 2012. A method to improve satellite soil moisture retrievals based on Fourier analysis. *Geophysical Research Letters* **39**: L15404. DOI: 10.1029/2012GL052435

Eliasson I, Homer B. 1990. Urban Heat Island circulation in Göteborg, Sweden. *Theoretical and Applied Climatology* **42**: 187–196.

Entekhabi D, Njoku E, O'Neill P, Kellogg K, Crow W, Edelstein W, Entin J, Goodman S, Jackson T, Johnson J, Kimball J, Piepmeier J, Koster R, McDonald K, Moghaddam M, Moran S, Reichle R, Shi JC, Spencer M, Thurman S, Tsang L, Van Zyl J. 2010. The Soil Moisture Active and Passive (SMAP) mission. *Proceedings of the Institute of Electrical and Electronics Engineers* **98**: 704–716.

Fall S, Niyogi D, Gluhovsky A, Pielke RA Sr, Kalnay E, Rochon G. 2010. Impacts of land use land cover on temperature trends over the continental United States: assessment using the North American Regional Reanalysis. *International Journal of Climatology* **30**: 1980–1993. DOI: 10.1002/joc.1996

Famiglietti JS, Lo M, Ho SL, Bethune J, Anderson KJ, Syed TH, Swenson SC, de Linage CR, Rodell M. 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters* **38**: L03403. DOI: 10.1029/2010GL046442

FAO. 2011. *State of the World's Forests 2011*. United Nations Publications: Rome; 179.

Feddema JJ, Oleson KW, Bonan GB, Mearns LO, Buja LE, Meehl GA, Washington WM. 2005. The Importance of land-cover change in simulating future climates. *Science* **310**: 1674–1678.

Findell KL, Knutson TR, Milly PCD. 2006. Weak simulated extratropical responses to complete tropical deforestation. *Journal of Climate* **19**: 2835–2850.

Findell KL, Shevliakova E, Milly PCD, Stouffer RJ. 2007. Modeled impact of anthropogenic land cover change on climate. *Journal of Climate* **20**: 3621–3634.

Fisch G, Wright JR, Bastable HG. 1994. Albedo of tropical grass: a case study of pre- and post-burning. *Journal of Climatology* **14**: 103–118.

Foley JA, Coe MT, Scheffer M, Wang G. 2003a. Regime shifts in the Sahara and Sahel: interactions between ecological and climatic systems in Northern Africa. *Ecosystems* **6**: 524–532.

Foley JA, Delire C, Ramankutty N, Snyder P. 2003b. Green Surprise? How terrestrial ecosystems could affect earth's climate. *Frontiers in Ecology and the Environment* **1**: 38–44.

Franchito SH, Rao VB. 1992. Climatic change due to land surface alterations. *Climatic Change* **22**: 1–34.

Fu C. 2003. Potential impacts of human-induced land cover change on East Asia monsoon. *Global and Planetary Change* **37**: 219–229.

Fu C, Yasunari T, Lütkemeier S. 2004. The Asian Monsoon Climate. In *Vegetation, Water, Humans and Climate: A New Perspective on an Interactive System*, Claussen P, Dirmeyer M, Gash JHC, Kabat P, *et al.* (eds). Springer-Verlag: Berlin; 115–127.

Fujibe F. 2010. Day-of-the-week variations of urban temperature and their long-term trends in Japan. *Theoretical and Applied Climatology* **102**: 393–401.

Fujibe F, Asai T. 1984. A detailed analysis of the land and sea breeze in the Sagami Bay area in summer. *Journal of the Meteorological Society of Japan* **62**: 534–551.

Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger SP, Asner GP, Cleveland CC, Green PA, Holland EA, Karl DM, Michaels AF, Porter JH, Towensend AR, Vörösmarty CJ. 2004. Nitrogen cycles: past, present, and future. *Biogeochemical Cycles* **70**: 153–226. DOI: 10.1007/s10533-004-0370-0

Gameda S, Qian B, Campbell CA, Desjardins RL. 2007. Climatic trends associated with summer fallow in the Canadian Prairies. *Agricultural and Forest Meteorology* **142**: 170–185.

Garratt JR. 1993. Sensitivity of climate simulations to land-surface and atmospheric boundary layer treatments – A review. *Journal of Climate* **6**: 419–449.

Ge J. 2010. MODIS observed impacts of intensive agriculture on surface temperature in the southern Great Plains. *International Journal of Climatology* **30**: 1994–2003.

Gedney N, Valdes PJ. 2000. The effect of Amazonian deforestation on the Northern Hemisphere circulation and climate. *Geophysical Research Letters* **27**: 3053–3056. DOI: 10.1029/2000GL011794

Geerts B. 2002. On the effect of irrigation and urbanization on the annual range of monthly-mean temperatures. *Theoretical and Applied Climatology* **72**: 157–163.

Georgakis C, Santamouris M, Kaisarlis G. 2010. The vertical stratification of air temperature in the Center of Athens. *Journal of Applied Meteorology and Climatology* **49**: 1219–1232.

Gero AF, Pitman AJ, Narisma GT, Jacobson C, Pielke RA Sr. 2006. The impact of land cover change on storms in the Sidney Basin, Australia. *Global and Planetary Change* **54**: 57–78.

Givati A, Rosenfeld D. 2004. Quantifying precipitation suppression due to air pollution. *Journal of Applied Meteorology* **43**: 1038–1056.

Goldewijk KK. 2001. Estimating global land use change over the past 300 years: the HYDE Database. *Global Biogeochemical Cycles* **15**: 417–433.

Gordon LJ, Steffen W, Jonsson BF, Folke C, Falkenmark M, Johannessen A. 2005. Human modification of global water vapor flows from the land surface. *Proceedings of the National Academy of Sciences of the United States of America* **102**: 7612–7617.

Grau HR, Aide M. 2008. Globalization and land-use transitions in Latin America. *Ecology and Society* **13**: 16.

Grimmond CSB, Oke TR. 1995. Comparison of heat fluxes from summertime observations in the suburbs of four North American cities. *Journal of Applied Meteorology* **34**: 873–889.

Grossman-Clarke S, Zehnder JA, Loridan T, Grimmond CSB. 2010. Contribution of land use changes to near-surface air temperatures during recent summer extreme heat events in the Phoenix metropolitan area. *Journal of Applied Meteorology and Climatology* **49**: 1649–1664.

Guimberteau M, Laval K, Perrier A, Polcher J. 2011. Global effect of irrigation and its impact on the onset of the Indian summer monsoon. *Climate Dynamics* **39**: 1329–1348. DOI: 10.1007/s00382-011-1252-5

Guo X, Fu D, Wang J. 2006. Mesoscale convective precipitation system modified by urbanization in Beijing city. *Atmospheric Research* **82**: 112–126.

Hale RC, Gallo KP, Owen TW, Loveland TR. 2006. Land use/land cover change effects on temperature trends at U.S. Climate Normals stations. *Geophysical Research Letters* **33**: L11703. DOI: 10.1029/2006GL026358

Hale RC, Gallo KP, Loveland TR. 2008. Influences of specific land use/land cover conversions on climatological normals of near-surface temperature. *Journal of Geophysical Research* **113**: D14113. DOI: 10.1029/2007JD009548

Han JY, Baik JJ. 2008. A theoretical and numerical study of urban heat island-induced circulation and convection. *Journal of the Atmospheric Sciences* **65**: 1859–1877.

Hand L, Shepherd JM. 2009. An investigation of warm season spatial rainfall variability in Oklahoma City: possible linkages to urbanization and prevailing wind. *Journal of Applied Meteorology and Climatology* **48**: 251–269.

Hanna S, Marciotto E, Britter R. 2011. Urban energy fluxes in built-up downtown areas and variations across the urban area, for use in dispersion models. *Journal of Applied Meteorology and Climatology* **50**: 1341–1353. DOI: 10.1175/2011JAMC2555.1

Hansen MC, Stehman SV, Potapova PV, Loveland TR, Townshend JRG, DeFries RS, Pittman KW, Arunarwati B, Stolle F, Steininger MK, Carroll M, DiMiceli C. 2008. Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data. *Proceedings of the National Academy of Sciences of the United States of America* **105**: 9439–9444.

Hansen MC, Stehman SV, Potapova PV. 2010. Quantification of global gross forest cover loss. *Proceedings of the National Academy of Sciences of the United States of America* **107**: 8650–8655.

Harding DJ, Carabajal CC. 2005. ICESat waveform measurements of within-footprint topographic relief and vegetation vertical structure. *Geophysical Research Letters* **32**: L21S10. DOI: 10.1029/2005GL023471

Hasler N, Werth D, Avissar R. 2009. Effects of tropical deforestation on global hydroclimate: a multimodel ensemble analysis. *Journal of Climate* **22**: 1124–1141.

Hatfield JL, Prueger JH, Kustas WP. 2007. Spatial and temporal variation of energy and carbon dioxide fluxes in corn and soybean fields in central Iowa. *Agronomy Journal* **99**: 285–296.

Heck P, Lüthi D, Wernli H *et al.* 2001. Climate impacts of European-scale anthropogenic vegetation changes: a sensitivity study using a regional climate model. *Journal of Geophysical Research* **106**: 7817–7835. DOI: 10.1029/2000JD900673

van den Heever SC, Cotton WR. 2007. Urban aerosol impacts on downwind convective storms. *Journal of Applied Meteorology and Climatology* **46**: 828–850.

Henderson-Sellers A, Dickinson RE, Durbidge TB, Kennedy PJ, McGuffie K, Pitman AJ. 1993. Tropical deforestation: modeling local- to regional-scale climate change. *Journal of Geophysical Research* **98**: 7289–7315.

Hidalgo J, Masson V, Baklanov A, Pigeon G, Gimenoa L. 2008. Advances in urban climate modeling: trends and directions in climate research. *Annals of the New York Academy of Sciences* **1146**: 354–374.

Hinkel KM, Nelson FE. 2007. Anthropogenic heat island at Barrow, Alaska, during winter: 2001–2005. *Journal of Geophysical Research* **112**: D06118. DOI: 10.1029/2006JD007837

Hirota M, Nobre C, Oyama MD, Bustamante MMC. 2010. The climatic sensitivity of the forest, savanna and forest–savanna transition in tropical South America. *New Phytologist* **187**: 707–719.

Hoffman WA, Jackson RB. 2000. Vegetation-climate feedbacks in the conversion of tropical savanna to grassland. *Journal of Climate* **13**: 1593–1602.

Howard L. 1820. *Climate of London Deduced From Meteorological Observations*. Harvey and Darton: London.

Hu Y, Dong W, He Y. 2010. Impact of land surface forcings on mean and extreme temperature in eastern China. *Journal of Geophysical Research* **115**: D19117. DOI: 10.1029/2009JD013368

Huff FA, Vogel JL. 1978. Urban, topographic and diurnal effects on rainfall in the St. Louis region. *Journal of Applied Meteorology* **17**: 565–577.

Imhoff M, Zhang P, Wolfe RE, Bounoua L. 2010. Remote sensing of the urban heat island effect across biomes in the continental USA. *Remote Sensing of Environment* **114**: 504–513. DOI: 10.1016/j.rse.2009.10.008

IPCC. 2012. Summary for policymakers. In *IntergovernmentalPanel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds.) Cambridge University Press: Cambridge/New York.

Jackson RB, Jobbágy EG, Avissar R, Baidya Roy S, Barrett DJ, Cook CW, Farley KA, le Maitre DC, McCarl BA, Murray BC. 2005. Trading water for carbon with biological carbon sequestration. *Science* **310**: 1944–1947.

Jackson TL, Feddema JJ, Oleson KW, Bonan GB, Bauer JT. 2010. Parameterization of urban characteristics for global climate modeling. *Annals of the Association of American Geographers* **100**: 848–865.

Jansson C, Jansson P-E, Gustafsson D. 2007. Near surface climate in an urban vegetated park and its surroundings. *Theoretical and Applied Climatology* **89**: 185–193.

Jin J, Miller NL. 2011. Regional simulations to quantify land use change and irrigation impacts on hydroclimate in the California Central Valley. *Theoretical and Applied Climatology* **104**: 429–442.

Jin M, Shepherd JM, Peters-Lidard C. 2007. Development of a parameterization for simulating the urban temperature hazard using satellite observations in climate model. *Natural Hazards* **43**: 257–271.

Jones C, Lowe J, Liddicoat S, Betts R. 2009. Committed terrestrial ecosystem changes due to climate change. *Nature Geoscience* **2**: 484–487.

Jonko AK, Hense A, Feddema JJ. 2010. Effects of land cover change on the tropical circulation in a GCM. *Climate Dynamics* **35**: 635–649.

Juang J-Y, Katul G, Siqueira M, Stoy P, Novick K. 2007. Separating the effects of albedo from eco-physiological changes on surface temperature along a successional chronosequence in the southeastern United States. *Geophysical Research Letters* **34**: L21408. DOI: 10.1029/2007GL031296

Junkermann W, Hacker J, Lyons T, Nair US. 2009. Land use change suppresses precipitation. *Atmospheric Chemistry and Physics* **9**: 11481–11500.

Justice CO, Townshend JRG, Choudhury BJ. 1989. Comparison of AVHRR and SMMR data for monitoring vegetation phenology on a continental scale. *International Journal of Remote Sensing* **10**: 1607–1632.

Kabat P, Claussen M, Dirmeyer PA, Gash JHC, de Guenni LB, Meybeck M, Pielke RA Sr, Vorosmarty CJ, Hutjes RWA, Lutkemeier S. 2004. *Vegetation, Water, Humans and the Climate: A New Perspective on an Interactive System*. Springer Global Change - The IGBP Series, 566 pp: Berlin.

Kalnay E, Cai M. 2003. Impact of urbanization and land use on climate change. *Nature* **423**: 528–531.

Karl TR, Diaz HF, Kukla G. 1988. Urbanization: its detection and effect in the United States climate record. *Journal of Climate* **1**: 1099–1123.

Kaufmann RK, Seto KC, Schneider A, Liu Z, Zhou L, Wang W. 2007. Climate response to rapid urban growth: evidence of a human-induced precipitation deficit. *Journal of Climate* **20**: 2299–2306.

Kawai T, Ridwan MK, Kanda M. 2009. Evaluation of the simple urban energy balance model using selected data from 1-yr flux observations at two cities. *Journal of Applied Meteorology and Climatology* **48**: 693–715.

Kerr YH, Waldteufel P, Wigneron J-P, Delwart S, Cabot F, Boutin J, Escorihuela M-J, Font J, Reul N, Gruhier C, Juglea SE, Drinkwater M, Hahne A, Martin-Neira M, Mecklenburg S. 2010. The SMOS mission: new tool for monitoring key elements of the global water cycle. *Proceedings of the Institute of Electrical and Electronics Engineers* **98**: 666–687.

Keys PW, van der Ent RJ, Gordon LJ, Hoff H, Nikoli R, Savenije HHG. 2012. Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences* **9**: 733–746.

Kishtawal C, Niyogi D, Tewari M, Pielke RA Sr, Shepherd M. 2010. Urbanization signature in the observed heavy rainfall climatology over India. *International Journal of Climatology* **30**: 1908–1916. DOI: 10.1002/joc.2044

Kitoh A, Yamazaki K, Tokioka T. 1988. Influence of soil moisture and surface albedo changes over the African tropical rain forest on summer climate investigated with the MRI-GCM-I. *Journal of the Meteorological Society of Japan* **66**: 65–85.

Klingman NP, Butke J, Leathers DJ, Brinson KR, Nickle E. 2008. Mesoscale simulations of the land surface effects of historical logging in a moist continental climate regime. *Journal of Applied Meteorology and Climatology* **47**: 2166–2182.

Kueppers LM, Snyder MA, Sloan LC. 2007. Irrigation cooling effect: regional climate forcing by land-use change. *Geophysical Research Letters* **34**: L03703. DOI: 10.1029/2006GL028679

Kueppers LM, Snyder MA, Sloan LC, Cayan D, Jin J, Kanamaru H, Kanamitsu M, Miller NL, Tyree M, Du H, Weare B. 2008. Seasonal temperature responses to land-use change in the western United States. *Global and Planetary Change* **60**: 250–264.

Kukla G, Gavin J, Karl TR. 1986. Urban warming. *Journal of Climate and Applied Meteorology* **25**: 1265–1270.

Kvalevåg M, Myhre G, Bonan G, Levis S. 2010. Anthropogenic land cover changes in a GCM with surface albedo changes based on MODIS data. *International Journal of Climatology* **30**: 2105–2117.

Lamarque J-F, Kiehl J, Brasseur G, Butler T, Cameron-Smith P, Collins WD, Collins WJ, Granier C, Hauglustaine D, Hess P, Holland E, Horowitz L, Lawrence M, McKenna D, Merilees P, Prather M, Rasch P, Rotman D, Shindell D, Thornton P. 2005. Assessing future nitrogen deposition and carbon cycle feedback using a multimodel approach: analysis of nitrogen deposition. *Journal of Geophysical Research* **110**: D19303. DOI: 10.1029/2005JD005825

Lambin EF, Geist HJ, Lepers E. 2003. Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources* **28**: 205–241.

Landsberg HE. 1970. Man-made climate changes. *Science* **170**: 1265–1274.

Lapola DM, Oyama MD, Nobre CA. 2009. Exploring the range of climate biome projections for tropical South America: the role of CO_2 fertilization and seasonality. *Global Biogeochemical Cycles* **23**: GB3003. DOI: 10.1029/2008GB003357

Lawrence PJ, Chase TN. 2010. Investigating the climate impacts of global land cover change in the Community Climate System Model (CCSM). *International Journal of Climatology* **30**: 2066–2087.

Lawrence PJ, Feddema JJ, Bonan GB, Meehl GA, O'Neill BC, Oleson KW, Levis S, Lawrence DM, Kluzek E, Lindsay K, Thornton PE. 2012. Simulating the biogeochemical and biogeophysical impacts of transient land cover change and wood harvest in the Community Climate System Model (CCSM4) from 1850 to 2100. *Journal of Climate* **25**: 3071–3095.

Lee E, Chase TN, Rajagopalan B. 2008. Highly improved predictive skill in the forecasting of the East Asian summer monsoon. *Water Resources Research* **44**: W10422. DOI: 10.1029/2007WR006514

Lee E, Chase TN, Rajagopalan B, Barry RG, Biggs TW, Lawrence PJ. 2009. Effects of irrigation and vegetation activity on early Indian summer monsoon variability. *International Journal of Climatology* **29**: 573–581.

Lee E, Sacks WJ, Chase TN, Foley J. 2011. Simulated impacts of irrigation on the atmospheric circulation over Asia. *Journal of Geophysical Research* **116**: D08114. DOI: 10.1029/2010JD014740

Leeper R, Mahmood R, Quintanar AI. 2009. Near surface atmospheric response to simulated changes in land-cover, vegetation fraction, and soil moisture over Western Kentucky. *Publications in Climatology* **62**: 41.

Lefsky MA, Cohen WB, Parker GG, Harding JJ. 2002. LiDAR remote sensing for ecosystem studies. *BioScience* **52**: 19–30.

Lefsky MA, Harding DJ, Keller M, Cohen WB, Carabajal CC, Del Bom Espirito-Santo F, Hunter MO, de Oliveira R Jr. 2005. Estimates of forest canopy height and aboveground biomass using ICESat. *Geophysical Research Letters* **32**: L22S02. DOI: 10.1029/2005GL023971

Lefsky MA, Keller M, Pang Y, de Camargo P, Hunter MO. 2007. Revised method for forest canopy height estimation from the Geoscience Laser Altimeter System waveforms. *Journal of Applied Remote Sensing* **1**: 013537.

Legates DR. 1987. A climatology of global precipitation. *Publications in Climatology* **40**: 84.

Legates DR. 1995. Precipitation measurement biases and climate change detection. In *Proceedings of the Sixth Symposium on Global Change Studies*. American Meteorological Society, Dallas, TX, 168–173.

Legates DR, Willmott CJ. 1990. Mean seasonal and spatial variability in gauge-corrected, global precipitation. *International Journal of Climatology* **10**: 111–127.

Lei M, Niyogi D, Kishtawal C, Pielke R Sr, Beltrán-Przekurat A, Nobis T, Vaidya S. 2008. Effect of explicit urban land surface representation on the simulation of the 26 July 2005 heavy rain event over Mumbai, India. *Atmospheric Chemistry and Physics* **8**: 8773–8816.

Lemonsu A, Grimmond CSB, Masson V. 2004. Modeling the surface energy balance of the core of an old Mediterranean city: Marseille. *Journal of Applied Meteorology* **43**: 312–327.

Lensky IM, Drori R. 2007. A satellite-based parameter to monitor the aerosol impact on convective clouds. *Journal of Applied Meteorology and Climatology* **46**: 660–666.

Lo JCF, Lau AKH, Chen F, Chen F, Fung JCH, Leung KKM. 2007. Urban modification in a mesoscale model and the effects on the local circulation in the Pearl River Delta region. *Journal of Applied Meteorology and Climatology* **46**: 457–476.

Lobell DB, Bonfils C. 2008. The effect of irrigation on regional temperatures: a spatial and temporal analysis of trends in California, 1934–2002. *Journal of Climate* **21**: 2064–2071.

Lobell DB, Bala G, Duffy PB. 2006a. Biogeophysical impacts of cropland management changes on climate. *Geophysical Research Letters* **33**: L06708. DOI: 10.1029/2005GL025492

Lobell DB, Bala G, Bonfils C, Duffy PB. 2006b. Potential bias of model projected greenhouse warming in irrigated regions. *Geophysical Research Letters* **33**: L13709. DOI: 10.1029/2006GL026770

Lobell D, Bala G, Mirin A, Phillips T, Maxwell R, Rotman D. 2009. Regional differences in the influence of irrigation on climate. *Journal of Climate* **22**: 2248–2255.

Lofgren BM. 1995. Surface albedo-climate feedback simulated using two-way feedback. *Journal of Climate* **8**: 2543–2562.

Lohar D, Pal B. 1995. The effect of irrigation on premonsoon season over southwest Bengal, India. *Journal of Climate* **8**: 2567–2570.

Loridan T, Grimmond CSB. 2012. Characterization of energy flux partitioning in urban environments: links with surface seasonal properties. *Journal of Applied Meteorology and Climatology* **51**: 219–241.

Lyons TJ. 2002. Clouds prefer native vegetation. *Meteorology and Atmospheric Physics* **80**: 131–140.

Lyons TJ, Schwerdtfeger P, Hacker JM, Foster IJ, Smith RGC, Xinmei H. 1993. Land atmosphere interaction in a semiarid region – the Bunny Fence experiment. *Bulletin of the American Meteorological Society* **74**: 1327–1334.

Lyons TJ, Nair US, Foster IJ. 2008. Clearing enhances dust devil formation. *Journal of Arid Environments* **72**: 1918–1928.

Mahmood R, Hubbard KG. 2002. Anthropogenic land use change in the North American Tall Grass-Short grass transition and modification of near surface hydrologic cycle. *Climate Research* **21**: 83–90.

Mahmood R, Hubbard KG, Carlson C. 2004. Modification of growing-season surface temperature records in the Northern Great Plains due to land use transformation: verification of modeling results and implications for global climate change. *International Journal of Climatology* **24**: 311–327.

Mahmood R, Foster SA, Keeling T, Hubbard KG, Carlson C, Leeper R. 2006. Impacts of irrigation on 20th-century temperatures in the Northern Great Plains. *Global and Planetary Change* **54**: 1–18.

Mahmood R, Hubbard KG, Leeper R, Foster SA. 2008. Increase in near surface atmospheric moisture content due to land use changes: evidence from the observed dew point temperature data. *Monthly Weather Review* **136**: 1554–1561.

Mahmood R, Pielke RA Sr, Hubbard KG, Niyogi D, Bonan G, Lawrence P, McNider R, McAlpine C, Etter A, Gameda S, Qian B, Carleton A, Beltran-Przekurat A, Chase T, Quintanar AI, Adegoke JO, Vezhapparambu S, Conner G, Asefi S, Sertel E, Legates DR, Wu Y, Hale R, Frauenfeld ON, Watts A, Shepherd M, Mitra C, Anantharaj VG, Fall S, Lund R, Nordfelt A, Blanken P, Du J, Chang H-I, Leeper R, Nair US, Dobler S, Deo R, Syktus J. 2010. Impacts of land use land cover change on climate and future research priorities. *Bulletin of the American Meteorological Society* **91**: 37–46.

Mahmood R, Leeper R, Quintanar AI. 2011. Sensitivity of planetary boundary layer atmosphere to historical and future changes of land use/land cover, vegetation fraction, and soil moisture in Western Kentucky, USA. *Global and Planetary Change* **78**: 36–53. DOI: 10.1016/j.gloplacha.2011.05.007

Masson V, Grimmond CSB, Oke TR. 2002. Evaluation of the Town Energy Balance (TEB) Scheme with direct measurements from dry districts in two cities. *Journal of Applied Meteorology* **41**: 1011–1026.

Matthews HD, Weaver AJ, Eby M, Meissner KJ. 2003. Radiative forcing of climate by historical land cover change. *Geophysical Research Letters* **30**: 1055. DOI: 10.1029/2002GL016098

Matthews HD, Weaver AJ, Meissner KJ, Gillett NP, Eby M. 2004. Natural and anthropogenic climate change: incorporating historical land cover change, vegetation dynamics and the global carbon cycle. *Climate Dynamics* **22**: 461–479.

McAlpine CA, Syktus JI, Deo RC, Lawrence PJ, McGowan HA, Watterson IG, Phinn SR. 2007. Modeling the impact of anthropogenic land cover change on Australia's regional climate. *Geophysical Research Letters* **34**: L22711. DOI: 10.1029/2007GL031524

McAlpine CA, Syktus JI, Ryan JG, Deo RC, McKeon GM, McGowan HA, Phinn SR. 2009. A continent under stress: interactions, feedbacks and risks associated with impact of modified land cover on Australia's climate. *Global Change Biology* **15**: 2206–2223.

McAlpine CA, Ryan JG, Seabrook L, Thomas S, Dargusch PJ, Syktus JI, Pielke RA Sr, Etter AE, Fearnside PM, Laurance WF. 2010. More than CO_2: A broader picture for managing climate change and variability to avoid ecosystem collapse. *Current Opinion in Environmental Sustainability* **2**: 334–346. DOI: 10.1016/j.cosust.2010.10.001

McCarthy MP, Best MJ, Betts RA. 2010. Climate change in cities due to global warming and urban effects. *Geophysical Research Letters* **37**: L09705. DOI: 10.1029/2010GL042845

McNider RT, Lapenta WM, Biazar A, Jedlovec G, Suggs R, Pleim J. 2005. Retrieval of grid scale heat capacity using geostationary satellite products: part I: case-study application. *Journal of Applied Meteorology* **88**: 1346–1360.

McPherson RA, Stensrud DJ, Crawford KC. 2004. The impact of Oklahoma's wheat belt on the mesoscale environment. *Monthly Weather Review* **132**: 405–421.

Mitra C, Shepherd JM, Jordan T. 2011. On the relationship between the premonsoonal rainfall climatology and urban land cover dynamics in Kolkata city, India. *International Journal of Climatology* **32**: 1443–1454. DOI: 10.1002/joc.2366

Mohr KI, Baker RD, Tao W-K, Famiglietti JS. 2003. The sensitivity of West African convective line water budgets to land cover. *Journal of Hydrometeorology* **4**: 62–76.

Mote TL, Lacke MC, Shepherd JM. 2007. Radar signatures of the urban effect on precipitation distribution: a case study for Atlanta, Georgia. *Geophysical Research Letters* **34**: L20710. DOI: 10.1029/2007GL031903

Murata A, Sasaki H, Hanafusa M, Kurihara K. 2012. Estimation of urban heat island intensity using biases in surface air temperature simulated by a nonhydrostatic regional climate model. *Theoretical and Applied Climatology* **112**: 351–361. DOI: 10.1007/s00704-012-0739-2

Mylne MF, Rowntree PR. 1992. Modeling the effects of albedo change associated with tropical deforestation. *Climatic Change* **21**: 317–343.

Nagendra H, Southworth J. 2010. Reforesting Landscapes: Linking Pattern and Process. Landscape Series, No. 10. Springer: Dordrecht, the Netherlands.

Nair US, Wu Y, Kala J, Lyons TJ, Pielke RA Sr, Hacker JM. 2011. The role of land use change on the development and evolution of the west coast trough, convective clouds, and precipitation in southwest Australia. *Journal of Geophysical Research* **116**: D07103. DOI: 10.1029/2010JD014950

Narisma GT, Pitman AJ. 2004. The effect of including biospheric responses to CO_2 on the impact of land-cover change over Australia. *Earth Interactions* **8**: 1–28.

Narisma GT, Pitman AJ, Eastman J, Watterson IG, Pielke R Sr, Beltrán-Przekurat A. 2003. The role of biospheric feedbacks in the simulation of the impact of historical land cover change on the Australian January climate. *Geophysical Research Letters* **30**: 2168. DOI: 10.1029/2003GL018261

Neale CMU, McFarland MJ, Chang K. 1990. Land surface-type classification using microwave brightness temperatures from the special sensor microwave/imager. *IEEE Transactions on Geoscience and Remote Sensing* **28**: 829–838.

Niyogi D, Holt T, Zhong S, Pyle PC, Basara J. 2006. Urban and land surface effects on the 30 July 2003 mesoscale convective system event observed in the southern Great Plains. *Journal of Geophysical Research* **111**: D19107. DOI: 10.1029/2005JD006746

Niyogi D, Kishtawal CM, Tripathi S, Govindaraju RS. 2010. Observational evidence that agricultural intensification and land use change may be reducing the Indian summer monsoon rainfall. *Water Resources Research* **46**: W03533. DOI: 10.1029/2008WR007082

Niyogi D, Pyle P, Lei M, Arya SP, Kishtawal CM, Shepherd M, Chen F, Wolfe B. 2011. Urban modification of thunderstorms: an observational storm climatology and model case study for the Indianapolis urban region. *Journal of Applied Meteorology and Climatology* **50**: 1129–1144.

Njoku EG. 1999. *AMSR Land Surface Parameters. Algorithm Theoretical Basis Document: Surface Soil Moisture, Land Surface Temperature, Vegetation Water Content, Version 3.0*. NASA Jet Propulsion Laboratory: Pasadena.

Nobre CA, Sellers PJ, Shukla J. 1991. Amazonian deforestation and regional climate change. *Journal of Climate* **4**: 957–988.

Nobre P, Malagutti M, Urbano DF, De Almeida RAF, Giarolla E. 2009. Amazon deforestation and climate change in a coupled model simulation. *Journal of Climate* **22**: 5686–5697.

Nosetto MD, Jobbagy EG, Paruelo JM. 2005. Land-use change and water losses: the case of grassland afforestation across a soil textural gradient in central Argentina. *Global Change Biology* **11**: 1101–1117.

NRC. 1992. *Grasslands and Grassland Sciences in Northern China*. The National Academies Press: Washington, D.C.; 214.

NRC. 2005. *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*. The National Academies Press: Washington, D.C.; 208.

NRC. 2012. *Urban Meteorology: Scoping the Problem, Defining the Need*. The National Academies Press: Washington, D.C.

Nuñez MN, Ciapessoni HH, Rolla A, Kalnay E, Cai M. 2008. Impact of land use and precipitation changes on surface temperature trends in Argentina. *Journal of Geophysical Research* **113**: D06111. DOI: 10.1029/2007JD008638

Offerle B, Jonsson P, Eliasson I, Grimmond CSB. 2005. Urban modification of the surface energy balance in the West African Sahel: Ouagadougou, Burkina Faso. *Journal of Climate* **18**: 3983–3995.

Offerle B, Grimmond CSB, Fortuniak K, Pawlak W. 2006. Intraurban differences of surface energy fluxes in a central European city. *Journal of Applied Meteorology and Climatology* **45**: 125–136.

Ohashi Y, Kida H. 2002. Local circulations developed in the vicinity of both coastal and inland urban areas: numerical study with a mesoscale atmospheric model. *Journal of Applied Meteorology* **41**: 30–45.

Ohashi Y, Kawabe T, Shigeta Y, Hirano Y, Kusaka H, Fudeyasu H, Fukao K. 2009. Evaluation of urban thermal environments in commercial and residential spaces in Okayama City, Japan, using the wet-bulb globe temperature index. *Theoretical and Applied Climatology* **95**: 279–289.

Oke TR. 1987. *Boundary Layer Climates*, 2nd edn. Routledge/John Wiley & Sons: London/New York.

Oleson KW, Bonan GB, Levis S, Vertenstein M. 2004. Effects of land use change on North American climate: impact of surface datasets and model biogeophysics. *Climate Dynamics* **23**: 117–132.
Oleson KW, Bonan GB, Feddema J, Vertenstein M. 2008a. An urban parameterization for a global climate model. Part II: sensitivity to input parameters and the simulated urban heat island in offline simulations. *Journal of Applied Meteorology and Climatology* **47**: 1061–1076.
Oleson KW, Bonan GB, Feddema J, Vertenstein M, Grimmond CSB. 2008b. An urban parameterization for a global climate model. Part I: formulation and evaluation for two cities. *Journal of Applied Meteorology and Climatology* **47**: 1038–1060.
Oleson KW, Bonan GB, Feddema J. 2010. Effects of white roofs on urban temperature in a global climate model. *Geophysical Research Letters* **37**: L03701. DOI: 10.1029/2009GL042194
Otterman J. 1974. Anthropogenic impact on the albedo of the earth. *Climatic Change* **1**: 137–155.
Otterman J, Chou M-D, Arking A. 1984. Effects of non-tropical forest cover on Earth. *Journal of Climate and Applied Meteorology* **23**: 762–767.
Ozdogan M, Rodell M, Beaudoing HK, Toll DL. 2010. Simulating the effects of irrigation over the United States in a land surface model based on satellite-derived agricultural data. *Journal of Hydrometeorology* **11**: 171–184.
Parton WJ, Schimel DS, Cole CV, Ojima DS. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal* **51**: 1173–1179.
Pereira HM, Leadley PW, Proneca V, Alkemade R, Scharlemann JPW, Fernandez-Manjarrés JF, Araújo MB, Balvanera P, Biggs R, Cheung WWL, Chini L, Cooper HD, Gilman EL, Guénette S, Hurtt GC, Huntington HP, Mace GM, Oberdorff T, Revenga C, Rodrigues P, Scholes RJ, Sumalia UR, Walpole M. 2010. Scenarios for global biodiversity in the 21st century. *Science* **330**: 1496–1501.
Peterson TC. 2003. Assessment of urban versus rural in situ surface temperatures in the contiguous United States: no difference found. *Journal of Climate* **16**: 2941–2959.
Philandras CM, Metaxas DA, Nastos PT. 1999. Climate variability and urbanization in Athens. *Theoretical and Applied Climatology* **63**: 65–72.
Phillips OL, Arago LEOC, Lewis S *et al.* 2009. Drought sensitivity of the Amazon Rainforest. *Science* **323**: 1344–1347.
Pielke RA Sr. 2001. Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Reviews of Geophysics* **39**: 151–177.
Pielke RA Sr, Avissar R. 1990. Influence of landscape structure on local and regional climate. *Landscape Ecology* **4**: 133–155.
Pielke RA, Zeng X. 1989. Influence on severe storm development of irrigated land. *National Weather Digest* **14**: 16–17.
Pielke RA Sr, Adegoke J, Beltran-Przekurat A, Hiemstra CA, Lin J, Nair US, Niyogi D, Nobis TE. 2007. An overview of regional land use and land cover impacts on rainfall. *Tellus Series B: Chemical and Physical Meteorology* **59**: 587–601.
Pielke RA, Pitman A, Niyogi D, Mahmood R, McAlpine C, Hossain F, Klein Goldewijk K, Nair U, Betts R, Fall S, Reichstein M, Kabat P, de Noblet-Ducoudré N. 2011. Land use/land cover changes and climate: modeling analysis and observational evidence. *WIREs Climate Change* **2**: 828–850.
Pitman AJ, de Noblet-Ducoudré N, Cruz FT, Davin EL, Bonan GB, Brovkin V, Claussen M, Delire C, Ganzeveld L, Gayler V, van den Hurk BJJM, Lawrence PJ, van der Molen MK, Müller C, Reick CH, Seneviratne SI, Strengers BJ, Voldoire A. 2009. Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. *Geophysical Research Letters* **36**: L14814. DOI: 10.1029/2009GL039076
Polcher J, Laval K. 1994a. The impact of African and Amazonian deforestation on tropical climate. *Journal of Hydrology* **155**: 389–405.
Polcher J, Laval K. 1994b. A statistical study of the regional impact of deforestation on climate in the LMD GCM. *Climate Dynamics* **10**: 205–219.
Pongratz J, Bounoua L, DeFries RS, Morton DC, Anderson LO, Mauser W, Klink CA. 2006. The impact of land cover change on surface energy and water balance in Mato Grosso, Brazil. *Earth Interactions* **10**: 1–17.
Pongratz J, Reick CH, Raddatz T, Claussen M. 2008. A reconstruction of global agricultural areas and land cover for the last millennium. *Global Biogeochemical Cycles* **22**: GB3018. DOI: 10.1029/2007GB003153
Pongratz J, Reick CH, Raddatz T, Claussen M. 2010. Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change. *Geophysical Research Letters* **37**: L08702. DOI: 10.1029/2010GL043010
Potter P, Ramankutty N, Bennett EM, Donner SD. 2010. Characterizing the spatial patterns of global fertilizer application and manure production. *Earth Interactions* **14**: 1–22.
Puma MJ, Cook BI. 2010. Effects of irrigation on global climate during the 20th century. *Journal of Geophysical Research* **115**: D16120. DOI: 10.1029/2010JD014122
Rabin RM, Stadler S, Wetzel PJ, Stensrud DJ, Gregory M. 1990. Observed effects of landscape variability on convective clouds. *Bulletin of the American Meteorological Society* **71**: 272–280.
Ramankutty N, Foley JA. 1999. Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochemical Cycles* **13**: 997–1027. DOI: 10.1029/1999GB900046
Ramankutty N, Delire C, Snyder P. 2006. Feedbacks between agriculture and climate: an illustration of the potential unintended consequences of human land use activities. *Global and Planetary Change* **54**: 79–93.
Ramankutty N, Evan AT, Monfreda C, Foley JA. 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles* **22**: GB1003. DOI: 10.1029/2007GB002952
Ray DK, Nair US, Welch RM, Han Q, Zeng J, Su W, Kikuchi T, Lyons TJ. 2003. Effects of land use in Southwest Australia. 1: observations of cumulus cloudiness and energy fluxes. *Journal of Geophysical Research* **108**(D14): 4414. DOI: 10.1029/2002JD002654
Ray DK, Welch RM, Lawton RO, Nair US. 2006. Dry season clouds and rainfall in northern Central America: implications for the Mesoamerican biological corridor. *Global and Planetary Change* **54**: 150–162.
Reale O, Dirmeyer PA. 2000. Modeling the effects of vegetation on Mediterranean climate during the Roman Classical Period. Part I: climate history and model sensitivity. *Global and Planetary Change* **25**: 163–184.
Reale O, Shukla J. 2000. Modeling the effects of vegetation on Mediterranean climate during the Roman classical period. Part II: high resolution model simulation. *Global and Planetary Change* **25**: 185–214.
Rodell M, Velicogna L, Famiglietti JS. 2009. Satellite-based estimates of groundwater depletion in India. *Nature* **460**: 999–1002. DOI: 10.1038/460789a
Rose LS, Stallins JA, Bentley M. 2008. Concurrent cloud-to-ground lightning and precipitation enhancement in the Atlanta, Georgia (USA) urban region. *Earth Interactions* **12**: 1–30.
Rosenfeld D. 1999. TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophysical Research Letters* **26**: 3105–3108.
Rosenfeld D. 2000. Suppression of rain and snow by urban and industrial air pollution. *Science* **287**: 1793–1796. DOI: 10.1126/science.287.5459.1793
Roy SB, Avissar R. 2002. Impact of land use/land cover change on regional hydrometeorology in Amazonia. *Journal of Geophysical Research* **107**: 1–12.
Rozoff CM, Cotton WR, Adegoke JO. 2003. Simulation of St. Louis, Missouri, land use impacts on thunderstorms. *Journal of Applied Meteorology* **42**: 716–738.
Running SW, Coughlan JC. 1988. A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes. *Ecological Modelling* **42**: 125–154.
Ryan JG, McAlpine CA, Ludwig JA. 2010. Integrated vegetation designs for enhancing water retention and recycling in agroecosystems. *Landscape Ecology* **25**: 1277–1288.
Sachiho AA, Kimura F, Kusaka H, Inoue T, Ueda H. 2012. Comparison of the impact of global climate changes and urbanization on summertime future climate in the Tokyo Metropolitan Area. *Journal of Applied Meteorology and Climatology* **51**: 1441–1454.
Sacks WJ, Cook BI, Buenning N, Levis S, Helkowski JH. 2009. Effects of global irrigation on the near-surface climate. *Climate Dynamics* **33**: 159–175.
Saeed F, Hagemann S, Jacob D. 2009. Impact of irrigation on the South Asian summer monsoon. *Geophysical Research Letters* **36**: L20711. DOI: 10.1029/2009GL040625
Sailor DJ. 1995. Simulated urban climate response to modifications in surface albedo and vegetative cover. *Journal of Applied Meteorology* **34**: 1694–1704.

Salazar LF, Nobre CA. 2010. Climate change and thresholds of biome shifts in Amazonia. *Geophysical Research Letters* **37**: L17706. DOI: 10.1029/2010GL043538

Salazar LF, Nobre CA, Oyama MD. 2007. Climate change consequences on the biome distribution in tropical South America. *Geophysical Research Letters* **34**: L09708. DOI: 10.1029/2007GL029695

Sampaio G, Nobre CA, Costa MH, Satyamurty P, Soares-Filho BS, Cardoso M. 2007. Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. *Geophysical Research Letters* **34**: L17709. DOI: 10.1029/2007GL030612

Sandstrom MA, Lauritsen RG, Changnon D. 2004. A central U. S. summer extreme dew point climatology (1949–2000). *Physical Geography* **25**: 191–207.

Satoh TS, Shimada T, Hoshi H. 1996. Modeling and simulation of the Tokyo urban heat island. *Atmospheric Environment* **30**: 3431–3442.

Scanlon BR, Reedy RC, Stonestrom DA, Prudic DE, Dennehy KF. 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology* **11**: 1577–1593. DOI: 10.1111/j.1365-2486.2005.01026.x

Scanlon BR, Jolly I, Sophocleous M, Zhang L. 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. *Water Resources Research* **43**: W03437. DOI: 10.1029/2006WR005486

Schneider EK, Fan M, Kirtman BP, Dirmeyer PA. 2006. *Potential Effects of Amazon Deforestation on Tropical Climate*, COLA Technical Report 226. Available from the Center for Ocean-Land-Atmosphere Studies, 4041 Powder Mill Road, Suite 302, Calverton, MD 20705 USA, 41 pp.

Segal M, Arritt RW. 1992. Non-classical mesoscale circulations caused by surface sensible heat flux gradients. *Bulletin of the American Meteorological Society* **73**: 1593–1604.

Segal M, Avissar R, McCumber MC *et al.* 1988. Evaluation of vegetation effects on the generation and modification of mesoscale circulations. *Journal of the Atmospheric Sciences* **45**: 2268–2292.

Segal M, Garratt JR, Kallos G, Pielke RA. 1989a. The impact of wet soil and canopy temperatures on daytime boundary-layer growth. *Journal of the Atmospheric Sciences* **46**: 3673–3684.

Segal M, Schreiber WE, Kallos G, Garratt JR, Rodi A, Weaver J, Pielke RA Sr. 1989b. The impact of crop areas in northeast Colorado on midsummer mesoscale thermal circulations. *Monthly Weather Review* **117**: 809–825.

Sen Roy S, Mahmood R, Niyogi D, Lei M, Foster SA, Hubbard KG, Douglas E, Pielke R Sr. 2007. Impacts of the agricultural Green Revolution–induced land use changes on air temperatures in India. *Journal of Geophysical Research* **112**: D21108. DOI: 10.1029/2007JD008834

Sen Roy S, Mahmood R, Quintanar AI, Gonzalez A. 2011. Impacts of irrigation on dry Season precipitation in India. *Theoretical and Applied Climatology* **104**: 193–207. DOI: 10.1007/s00704-010-0338-z

Sen OL, Wang B, Wang YQ. 2004a. Impacts of re-greening the desertified lands in northwestern China: implications from a regional climate model experiment. *Journal of the Meteorological Society of Japan* **82**: 1679–1693.

Sen OL, Wang Y, Wang B. 2004b. Impact of Indochina deforestation on the East Asian summer monsoon. *Journal of Climate* **17**: 1366–1380.

Shem W, Shepherd JM. 2009. On the impact of urbanization on summertime thunderstorms in Atlanta: two numerical model case studies. *Atmospheric Research* **92**: 172–189. DOI: 10.1016/j.atmosres.2008.09.013

Shepherd JM. 2006. Evidence of urban-induced precipitation variability in arid climate regimes. *Journal of Arid Environments* **67**: 607–628.

Shepherd JM, Pierce H, Negri AJ. 2002. Rainfall modification by major urban areas: observations from spaceborne rain radar on the TRMM Satellite. *Journal of Applied Meteorology* **41**: 689–701.

Shepherd JM, Carter WM, Manyin M, Messen D, Burian S. 2010a. The impact of urbanization on current and future coastal convection: a case study for Houston. *Environment and Planning B* **37**: 284–304.

Shepherd JM, Stallins JA, Jin M, Mote T. 2010b. Urbanization: impacts on clouds, precipitation, and lightning. In *Monograph on Urban Ecological Ecosystems*, Peterson J, Volder A (eds). American Society of Agronomy-Crop Science Society of America-Soil Science Society of America: Madison.

Shi X, McNider RT, Singh MP, England DE, Friedman MJ, Lapenta WM, Norris WB. 2005. On the behavior of the stable boundary layer and role of initial conditions. *Pure and Applied Geophysics* **162**: 1811–1829.

Shi JC, Jackson T, Tao J, Du JY, Bindlish R, Lu LX, Chen KS. 2008. Microwave vegetation indices for short vegetation covers from satellite passive microwave sensor AMSR-E. *Remote Sensing of Environment* **112**: 4285–4300.

Shreffler JH. 1978. Factors affecting dry deposition of SO_2 on forests and grasslands. *Atmospheric Environment* **12**: 1497–1503.

Shukla J, Nobre C, Sellers P. 1990. Amazon deforestation and climate change. *Science* **247**: 1322–1325.

Siebert S, Döll P, Hoogeveen J, Faures JM, Frenken K, Feick S. 2005. Development and validation of the global map of irrigation areas. *Hydrology and Earth System Sciences* **9**: 535–547.

Snyder PK. 2010. The influence of tropical deforestation on the Northern Hemisphere climate by atmospheric teleconnections. *Earth Interactions* **14**: 1–32.

Snyder PK, Delire AC, Foley JA. 2004. Evaluating the influence of different vegetation biomes on the global climate. *Climate Dynamics* **23**: 279–302.

Sorooshian S, Li J, Hsu K-L, Gao X. 2011. How significant is the impact of irrigation on the local hydroclimate in California's Central Valley? Comparison of model results with ground and remote sensing data. *Journal of Geophysical Research* **116**: D06102. DOI: 10.1029/2010JD014775

Souch C, Grimmond S. 2006. Applied climatology: urban climate. *Progress in Physical Geography* **30**: 270–279.

Spracklen DV, Arnold SR, Taylor CM. 2012. Observations of increased tropical rainfall preceded by air passage over forests. *Nature* **489**: 282–285.

Stallins JA, Rose S. 2008. Urban lightning: current research, methods, and the geographical perspective. *Geography Compass* **2**: 620–639.

Steyaert LT, Knox RG. 2008. Reconstructed historical land cover and biophysical parameters for studies of land-atmosphere interactions within the eastern United States. *Journal of Geophysical Research* **113**: D02101. DOI: 10.1029/2006JD008277

Stone B, Hess J, Frumkin H. 2010. Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities? *Environmental Health Perspectives* **118**(10): 1425–1428.

Strack JE, Pielke RA Sr, Steyaert LT, Knox RG. 2008. Sensitivity of June near-surface temperatures and precipitation in the eastern United States to historical land cover changes since European settlement. *Water Resources Research* **44**: W11401. DOI: 10.1029/2007WR00654

Strengers B, Müller C, Schaeffer M, Haarsma R, Severijns C, Gerten D, Schaphoff S, van den Houdt R, Oostenrijk R. 2010. Assessing 20th century climate–vegetation feedbacks of land-use change and natural vegetation dynamics in a fully coupled vegetation–climate model. *International Journal of Climatology* **30**: 2055–2065.

Sud YC, Chao WC, Walker GK. 1993. Dependence of rainfall on vegetation: theoretical considerations, simulation experiments, observations, and inferences from simulated atmospheric soundings. *Journal of Arid Environments* **25**: 5–18.

Sud YC, Walker GK, Kim J-H, Liston GE, Sellers PJ, Lau WK-M. 1996. Biogeophysical consequences of a tropical deforestation scenario: a GCM simulation study. *Journal of Climate* **9**: 3225–3247.

Takahashi HG, Yoshikane T, Hara M, Takata K, Yasunari T. 2010. High-resolution modelling of the potential impact of land-surface conditions on regional climate over Indochina associated with the diurnal precipitation cycle. *International Journal of Climatology* **30**: 2004–2020.

Takata K, Saito K, Yasunari T. 2009. Changes in the Asian monsoon climate during 1700–1850 induced by preindustrial cultivation. *Proceedings of the National Academy of Sciences of the United States of America* **106**: 9570–9575.

Ter Maat HW, Hutjes RWA, Ohba R, Ueda H, Bisselink B, Bauer T. 2006. Meteorological impact assessment of possible large scale irrigation in Southwest Saudi Arabia. *Global and Planetary Change* **54**: 183–201.

Townshend J, Justice CO, Choudhury BJ, Tucker CJ, Kalb VT, Goff TE. 1989. A comparison of SMMR and AVHRR data for continental land cover characterization. *International Journal of Remote Sensing* **10**: 1633–1642.

Townshend J, Justice CO, Li W, Gurney C, McManus J. 1991. Global land cover classification by remote sensing: present capabilities and future possibilities. *Remote Sensing of Environment* **35**: 243–255.

Trusilova K, Jung M, Churkina G, Karstens U, Heimann M, Claussen M. 2008. Urbanization impacts on the climate in Europe: numerical experiments by the PSU NCAR Mesoscale Model (MM5). *Journal of Applied Meteorology and Climatology* **47**: 1442–1455.

Trusilova K, Jung M, Churkina G. 2009. On climate impacts of a potential expansion of urban land in Europe. *Journal of Applied Meteorology and Climatology* **48**: 1971–1980.

Tuinenburg OA, Hutjes RWA, Jacobs CMJ, Kabat P. 2011. Diagnosis of local land-atmosphere feedbacks in India. *Journal of Climate* **24**: 251–266.

Twine TE, Kucharik CJ, Foley JA. 2004. Effects of land cover change on the energy and water balance of the Mississippi River basin. *Journal of Hydrometeorology* **5**: 640–655.

Unger J. 2004. Intra-urban relationship between surface geometry and urban heat island: review and new approach. *Climate Research* **27**: 253–264.

Voldoire A, Royer JF. 2004. Tropical deforestation and climate variability. *Climate Dynamics* **22**: 857–874.

Voldoire A, Royer JF. 2005. Climate sensitivity to tropical land surface changes with coupled versus prescribed SSTs. *Climate Dynamics* **24**: 843–862.

Vukovich FM, Dunn JW. 1978. Theoretical study of St-Louis heat island – some parameter variations. *Journal of Applied Meteorology* **17**(11): 1585–1594.

Waisenan PJ, Bliss NB. 2002. Changes in population and agricultural land in conterminous United States, 1790 to 1997. *Global Biogeochemical Cycles* **16**: 1137. DOI: 10.1029/2001GB001843

Wang J, Chagnon FJF, Williams ER, Betts AK, Renno NO, Machadod LAT, Bishta G, Knox R, Bras RL. 2009. Impact of deforestation in the Amazon basin on cloud climatology. *Proceedings of the National Academy of Sciences of the United States of America* **106**: 3670–3674.

Weaver CP, Avissar R. 2001. Atmospheric disturbances caused by human modification of the landscape. *Bulletin of the American Meteorological Society* **82**: 269–282.

Weaver CP, Baidya Roy S, Avissar R. 2002. Sensitivity of simulated mesoscale atmospheric circulations resulting from landscape heterogeneity to aspects of model configuration. *Journal of Geophysical Research* **107**: 8041.

Werth D, Avissar R. 2002. The local and global effects of Amazon deforestation. *Journal of Geophysical Research* **107**(D20): 8087. DOI: 10.1029/2001JD000717

Wisser D, Fekete BM, Vörösmarty CJ, Schumann AH. 2010. Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network-Hydrology (GTN-H). *Hydrological and Earth System Sciences* **14**: 1–24.

Wu Y, Raman S. 1997. Effect of land-use pattern on the development of low level jets. *Journal of Applied Meteorology* **36**: 573–590.

Xue Y. 1996. The impact of desertification in the Mongolian and the Inner Mongolian Grassland on the regional climate. *Journal of Climate* **9**: 2173–2189.

Xue Y, Shukla J. 1993. The influence of land surface properties on Sahel climate. Part I: desertification. *Journal of Climate* **6**: 2232–2245.

Xue Y, Shukla J. 1996. The influence of land surface properties on Sahel climate. Part II: afforestation. *Journal of Climate* **9**: 3260–3275.

Yoshikado H. 1994. Interaction of the sea breeze with urban heat islands of different sizes and locations. *Journal of the Meteorological Society of Japan* **72**: 139–142.

Yow DM. 2007. Urban heat islands: observations, impacts, and adaptation. *Geography Compass* **2**: 1227–1251.

Zeng N, Neelin JD. 1999. A land–atmosphere interaction theory for the tropical deforestation problem. *Journal of Climate* **12**: 857–872.

Zhang Y-K, Schilling KE. 2006. Increasing streamflow and baseflow in Mississippi River since the 1940s: effect of land use change. *Journal of Hydrology* **324**: 412–422.

Zhang C, Chen F, Miao S, Li Q, Xia X, Xuan CY. 2009a. Impacts of urban expansion and future green planting on summer precipitation in the Beijing metropolitan area. *Journal of Geophysical Research* **114**: D02116. DOI: 10.1029/2008JD010328

Zhang H, Gao X, Li Y. 2009b. Climate impacts of land-use change in China and its uncertainty in a global model simulation. *Climate Dynamics* **32**: 473–494.

Zhao M, Pitman AJ, Chase TN. 2001. The impact of land-cover change on the atmospheric circulation. *Climate Dynamics* **17**: 467–477.

Zheng X, Eltahir EAB. 1998. The role of vegetation in the dynamics of West African monsoons. *Journal of Climate* **11**: 2078–2096.

Zheng Y, Yu G, Qian Y, Miao M, Zeng X, Liu H. 2002. Simulations of regional climatic effects of vegetation change in China. *Quarterly Journal of the Royal Meteorological Society* **128**: 2089–2114.

Zhou Y, Shepherd JM. 2009. Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. *Natural Hazards* **52**: 639–668. DOI: 10.1007/s11069–009–9406-z

